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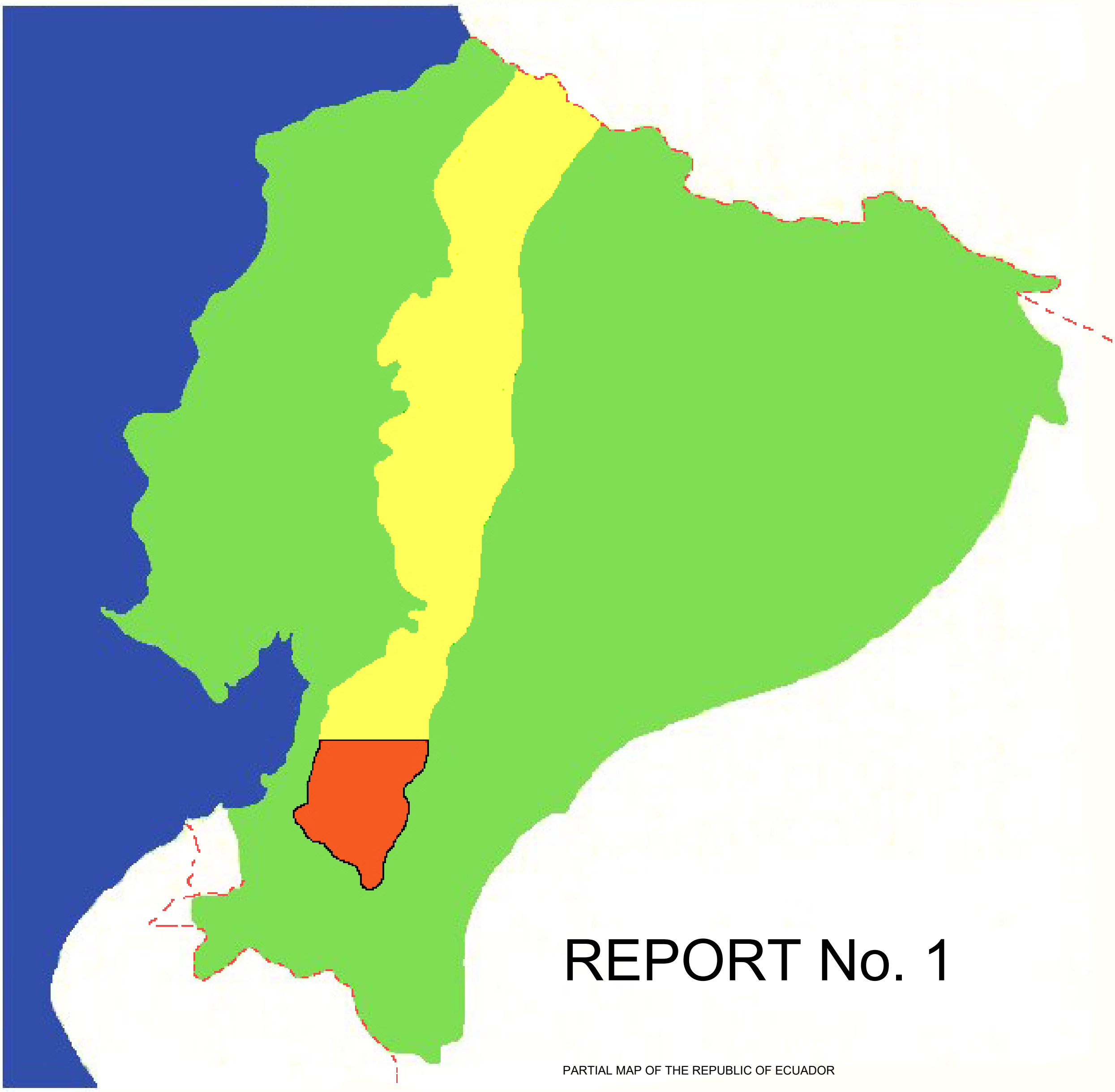

REPORT No. 1

PARTIAL MAP OF THE REPUBLIC OF ECUADOR

WORLD BANK MINING DEVELOPMENT AND ENVIRONMENTAL CONTROL PROJECT

GEOLOGICAL INFORMATION MAPPING PROGRAMME (WESTERN CORDILLERA)

PATRI MATRIQUE

MINING DEVELOPMENT AND ENVIRONMENTAL CONTROL PROJECT

GEOLOGICAL INFORMATION MAPPING PROGRAMME

Report Number 1

GEOLOGY OF THE WESTERN CORDILLERA OF ECUADOR BETWEEN 3°00’ AND 4°00’S

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CODIGEM-BRITISH GEOLOGICAL SURVEY

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1. INTRODUCTION

1.1 Background

This report describes the results of 1:50000 mapping in the Western Cordillera of Ecuador between latitudes 3°-4° south. The work was carried out as part of the Geological Mapping Information Programme, sub-component 3.3 of the Mining Development and Environmental Control Technical Assistance Project (PRODEMINCA). The wider project is funded by the World Bank, Department of International Development (DFID) (formerly the Overseas Development Administration) of the United Kingdom and the Swedish government. Geologists from the British Geological Survey (BGS) and Corporación de Desarrollo e Investigación Geológico-Minero-Metalúrgica (CODIGEM), as well as national consultants, were involved. The report complements a 1:200000 scale geological map of the area 5800 km^2 (Figure 1).

Lithostratigraphy has been constrained with 15 new dates (zircon fission track and K/Ar) from the study area (Appendix 1). Researches from the Swiss Federal Institute of Technology (EPN), Zurich have performed about 200 additional fission track dates in the intermontane basins of Southern Ecuador. These have aided the regional interpretations considerably. Whole rock geochemistry has been carried out on 21 samples (Appendix 2). 251 thin sections have been described (Appendix 3). A limited number of apparent magnetic susceptibility and scintillometer readings have been taken (Appendix 4).

Project policy was to use a combination of informal (units) and formal (groups and formations) stratigraphy and in general informal terms are used for the pre-Eocene lithostratigraphic sequences. New formations and the sources of the original definitions of existing formations are indicated in the title of each section. The lithostratigraphy has changed slightly from a preliminary scheme (Pratt et al., 1996). The time scale of Harland et al. (1989) is used. Structural symbols are in the format “010/56E” (strike/dip amount/dip direction).

1.2 Access and map coverage

1:50000 topographic maps are available from the Instituto Geográfico Militar (IGM). Aerial photography (IGM, 1:60000 scale) has been used to some extent, but is of poor quality. LANDSAT images were found to be useful for the drier, less incised areas. Examination of LANDSAT images acquired for mining companies indicates that clay-altered zones at mineral prospects show up if the data is processed with the correct bands. Specially acquired 1:100000 scale RADARSAT coverage, with a steep eastward “look” angle, to try and overcome the typical topographic distortion of radar, brings out some tectonic features that are visible by no other method. It also fills in the gaps left by cloud-covered LANDSAT and aerial photographs, especially in the foothills of the Western Cordillera.

Access is generally good. The Panamerican, Cuenca-Machala and Loja-Zaruma-Pasaje highways are the principal routes. Many new unsurfaced access roads provide access to villages, irrigation schemes and mining districts. However, large areas, such as between Ponce Enríquez and Uzhcurrumi and between the Chilla-Manú watershed and Zaruma, remain without road access. About 180 days, including mobilization, were spent mapping. More than 2500 km of roads and mule tracks have been studied, mainly in the drier “summer” (May-January) because the roads are poor during the rainy season. Vegetation varies from short grass, in the *páramo* above 3500 m to secondary jungle below 1000 m.

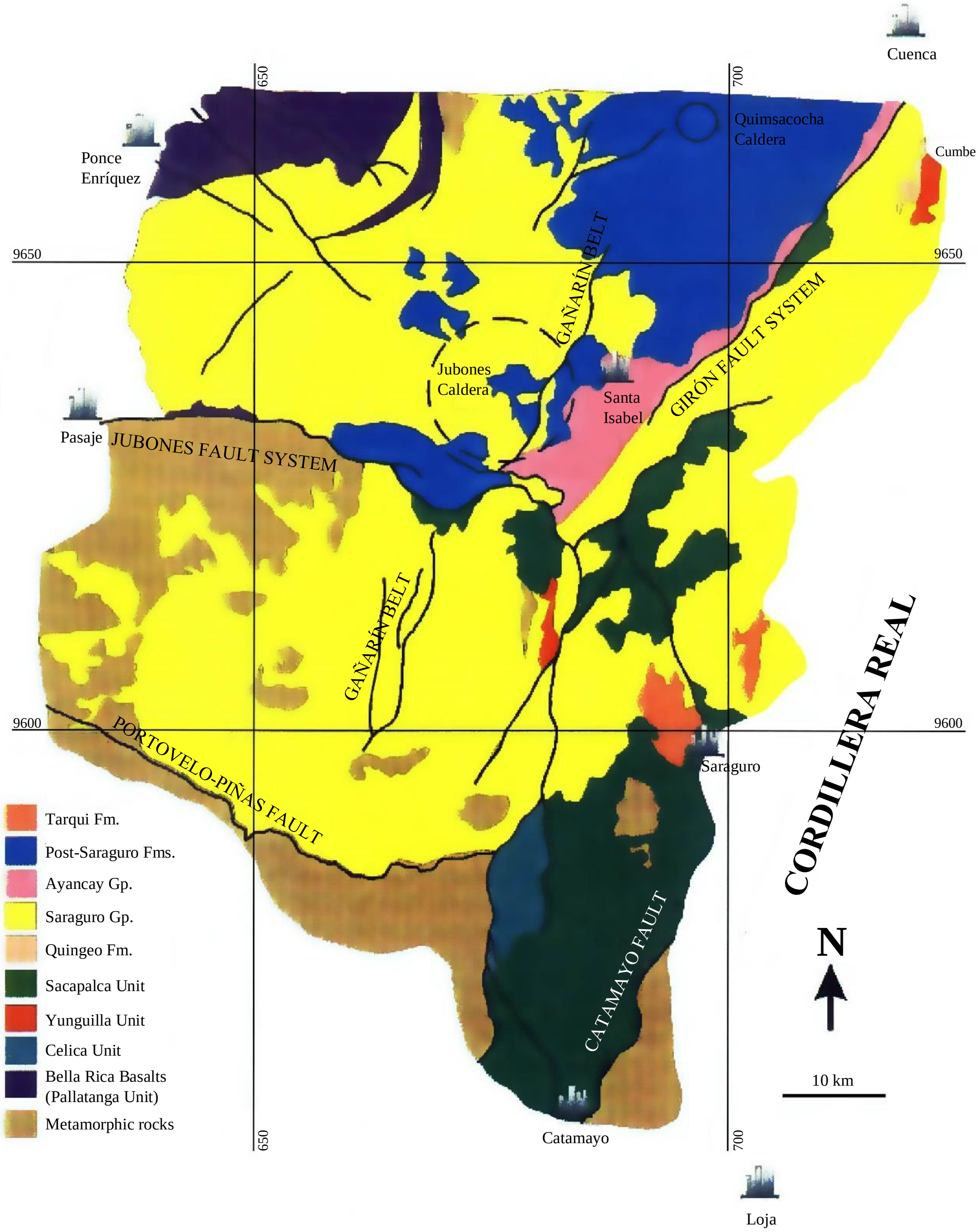

Figure 1. Location of the study area with simplified geology

1.3 Geological framework of Ecuador

Ecuador comprises three zones: the coastal plain (Costa), the Andean highlands (Sierra) and the Amazon Basin (Oriente). The Oriente is a sedimentary basin developed on a craton (Guyana Shield) and may be interpreted as a back-arc basin. The Sierra mainly comprises two mountain chains separated by a graben, although the division is ill-defined in the field area. The Cordillera Real, in the east, is made up of metamorphic rocks intruded by early Mesozoic, S and I-type granitoids. The Cordillera Occidental, in the west, probably comprises accreted terranes of arc rocks, oceanic crust and turbidite sequences which range from late Mesozoic to early Cenozoic. They are intruded by mid- to late Tertiary granitoids. Post-Eocene calc-alkaline volcanic rocks cover the older rocks. The Costa comprises Cretaceous oceanic crust overlain by Late Cretaceous to Cenozoic fore-arc sedimentary rocks.

1.4 Previous geological studies

Specific previous work is described in the appropriate sections. General references to Ecuadorian geology include Wolf (1892), Tschopp (1948, 1953) and Sauer (1957, 1965). The first 1:1000000 scale geological map (Servicio Nacional de Geología y Minería, 1969) resulted from studies of the petroleum basins, for example Faucher et al. (1968). From 1972 to 1980, cooperation between the Dirección General de Geología y Minas (DGGM) and the Institute of Geological Sciences (IGS) resulted in a series of 1:100000 maps and a new 1:1000000 national map (DGGM, 1982) and explanation (Baldock, 1982). Related publications on the geology and stratigraphy of Ecuador were those of Bristow and Hoffstetter (1977), Kennerley (1980), Bristow (1981) and Henderson (1979).

A second BGS-DGGM/INEMIN/CODIGEM project in the metamorphic Cordillera Real and El Oro province resulted in maps and memoirs (Litherland et al., 1994; Aspden et al., 1995) as well as new 1:1000000 geological and tectonometallogenic maps (BGS and CODIGEM, 1993a, b).

1.5 Acknowledgments

We would like to thank our Ecuadorian and British colleagues in the BGS and CODIGEM for their excellent technical back-up. Bill McCourt has expertly guided map production and symbology. Peter Dunkley kindly shared his volcanic expertise. The stream sediment sampling teams of Napoleón Báez, Johnson Bolaños and Edgar López, especially Freddy Núñez, Vinicio Ortiz, Holger Durazno, Luis Pilatasig, Jaime Galarza, Raúl Brito and Jorge Segovia brought back nearly 1000 well-located rock samples from remote sites. Their information strengthened the mapping programme considerably.

The mining community has provided information and facilitated fieldwork. In particular we thank Bernardo Beate (Cominecsa, Grantmining), Steve Bingham, Tor Bruland (Ecuanor), Oscar Dávila, Daniel Duzelier (COGEMA), Geoff Edwards and Germán Naranjo (Newmont), Fernando Gallardo and Les Smith (Grantmining), Rob Harley and Francisco Montes (Climax) and Guillermo López (Prominex). It is stressed, however, that all the following interpretations and metallogenic models are our opinions.

From the academic community, long discussions with Dominik Hungerbühler, Michael Steinmann and Wilfred Winkler of ETH Zürich, have been invaluable. This research group, through a combined sedimentological and fission track dating approach, has advanced the understanding of the intermontane basins of southern Ecuador considerably. They also undertook our fission track dating programme. Arturo Egüez, Escuela Politécnica Nacional-Quito, provided a very useful introduction to Ecuadorean geology.

Logistical back-up in CODIGEM has been excellent. Manuel Célleri has been the driver for all 10 field commissions. His local, and geological, knowledge have been invaluable. Freddy Núñez, Víctor Acitimbay, Fabiola Alcocer and Ricardo Rosales are thanked for drafting and secretarial work. John Aspden kindly collected some rock samples from Quebrada Florida. This report was edited by John Aspden, Peter Dunkley and Bill McCourt.

1.6 BGS publications

The LANDSAT and RADARSAT images are available for purchase. Tailored data processing (false colour composites, etc.) is available from the British Geological Survey. Enquiries related to map and report availability and coverage, as well as the purchase of LANDSAT and RADARSAT and other BGS services, should be directed to the International and Marketing Division, British Geological Survey, Keyworth, Nottingham, NG12 5GG, United Kingdom, Tel: 0115 936 3493, Fax: 0115 936 3520.

2. GEOLOGICAL SUMMARY

The El Oro metamorphic complex, comprising mainly metasedimentary rocks of very variable grade, is interpreted to extend north of the Jubones Fault System underlying much of the area. It is exposed in erosional windows both within the volcanic outcrop and around the edges (Figure 1). The metamorphic rocks are overlain by continental andesitic to rhyolitic tuffs and lavas (Celica Unit) and a thick Cretaceous turbidite sequence (Alamor Group/Yunguilla Unit) (Figure 2). They may also be overlain by Cretaceous basalts of the Pallatanga Unit, the Bella Rica basalts, although the evidence is equivocal. At Cumbe, south of Cuenca, the Yunguilla Unit has been dated as Maastrichtian and the Celica Unit is probably of Albian age.

Tertiary volcanic arc rocks, namely andesites of the Sacapalca Unit and the welded ash-flow tuffs of the Saraguro Group, dominate the field area. With contemporaneous sub-volcanic intrusions, these calc-alkaline products of subduction were deposited in an active tectonic environment which varied from extensional to compressional.

The Saraguro Group comprises alternations of broadly andesitic sequences, of a sedimentary character, and dacitic to rhyolitic ash-flow tuff sequences. The first are interpreted as outwashes on the flanks of andesitic volcanoes or fissures, and the second as ash-flows (outflow facies) from calderas. An extensive rhyolitic tuff, the Jubones Formation (earliest Miocene), occurs near the top of the Saraguro Group. Attaining 500 m, it covers approximately 2700 km^2, and has a volume of at least 350 km^3. It overlies older Saraguro rocks with strong angular unconformity in some places, indicating a phase of late Oligocene compression. The source caldera appears to lie southwest of Santa Isabel. At least two other major ash-flow tuffs are recognized the La Fortuna and La Paz Formations.

Post-Saraguro Group strata reflect the interplay of rivers/alluvial fans and primary, mainly andesitic, volcanism. Andesitic pyroclastic breccias, the Santa Isabel Formation, were erupted in the area of Santa Isabel. Afterwards, the Girón Fault System and Gañarín Belt constrained a Middle Miocene intermontane red-bed basin (Ayancay Group). Deposition of the red-beds began sometime around 18 Ma, initiating on the faulted, tilted and eroded basement of the Saraguro Group. The Santa Isabel and Jubones Formations were locally completely removed, so that red-beds lie directly on pre-Jubones strata. Andesitic volcanism also followed deposition of the red-beds, producing a complex situation whereby the red-beds are sandwiched between upper and lower tongues of andesites. The Santa Isabel Formation is overlain towards Cuenca by Late Miocene volcanoclastic and sedimentary rocks (Turi Formation).

The Quimsacocha Formation (Late Miocene-Pliocene?) emanated from the Quimsacocha volcano, which straddled the Gañarín Belt. The Pliocene-Pleistocene Tarqui Formation blankets all the older formations unconformably.

Coarse- to fine-grained quartz diorites and granodiorite-tonalites are widespread within the metamorphic basement, the Cretaceous Formations and in the deeper levels of the Saraguro Group and Sacapalca Unit. Syn-volcanic stocks of rhyolite and andesite are common in the Oligocene and younger strata.

Major northeast to north-northeast faults played a very important role throughout the geological history of the area. The two most important systems are the Gañarín Belt and the Girón Fault System. Simplistically, they constrained the intermontane basins, localized tectonic inversion, sited calderas and controlled epithermal mineralization.

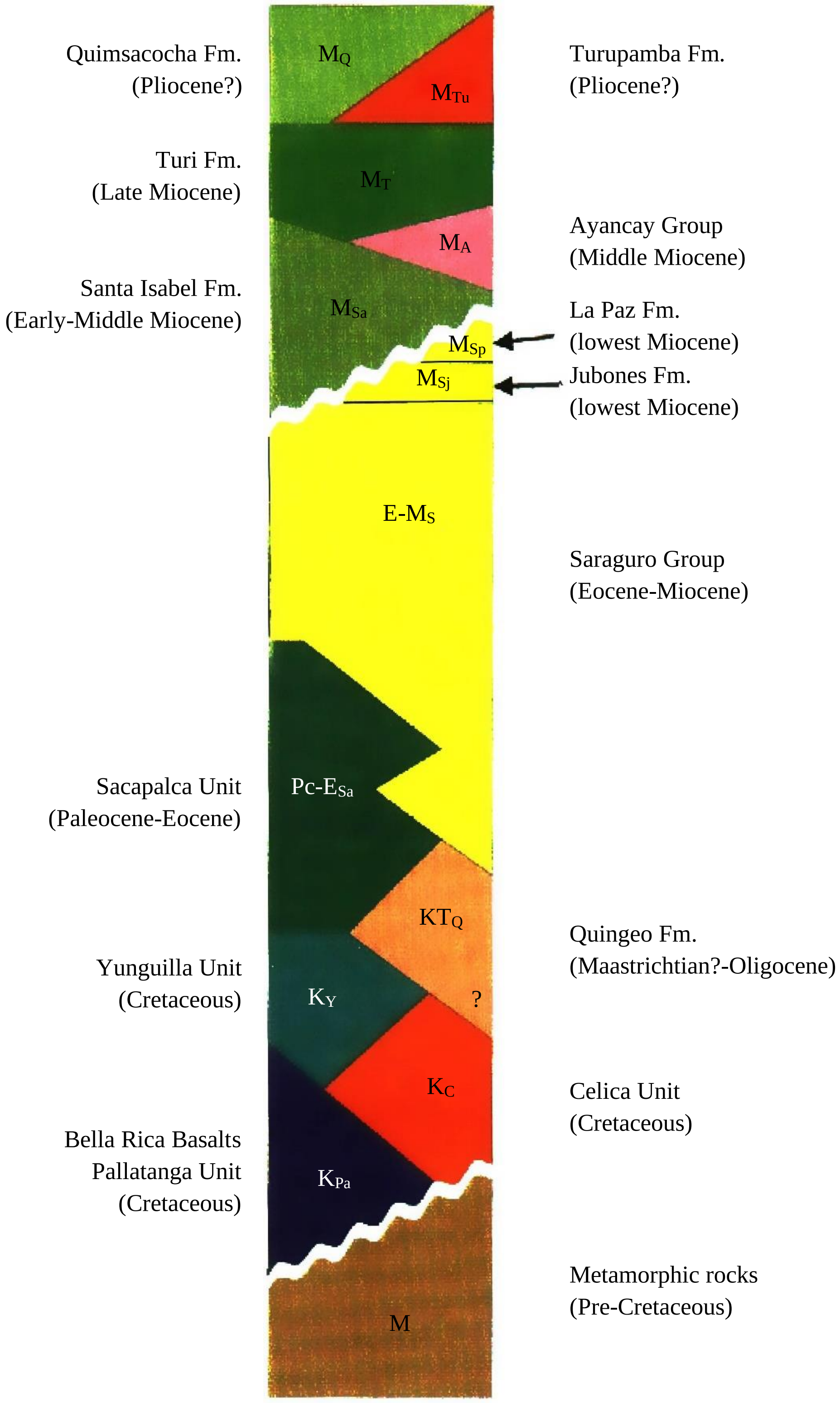

Figure 2. Simplified stratigraphical column. No scale implied

In general terms, the mineralization style changes from the foothills, where erosion has unroofed porphyries, mesothermal breccia pipes and mesothermal veins, to the high páramo, where there has been little erosion and epithermal deposits dominate. A five-fold classification is proposed:

a) Porphyry – mineralized porphyritic and non-porphyritic rhyolite to andesite (microdiorite) intrusions, commonly in intrusion complexes.

b) Epithermal deposits associated with rhyolite stocks, calderas and regional fractures.

c) Mesothermal tourmaline-, base metal- and gold-bearing veins and breccias.

d) Combined epithermal and mesothermal, base metal-poor, gold-bearing veins, locally rich in gold and with variable base metal content.

e) Massive sulphide deposits.

3. LITHOSTRATIGRAPHY

3.1 Undivided metamorphic rocks

Metamorphic rocks on the south and west sides of the volcanic outcrop belong to the El Oro metamorphic complex. A 1:50000 geological map (Feininger, 1978) and recent 1:100000 geological map and report (Aspden et al., 1995) cover these mainly metasedimentary rocks.

The El Oro metamorphic complex was examined in a road section in the south of the field area, between the Río Ambocas and El Cisne. This remarkable section demonstrates a rapid change in metamorphic grade without tectonic break or unconformity. Unmetamorphosed turbidites, previously included in the Cretaceous Alamor Group (Kennerley, 1973; DGGM, 1975a) and Triassic El Tigre Unit (Aspden et al., 1995), crop out at El Cisne [6735-95760]. The strata, estimated at about 1 km thick, are quartzose fine sandstones, locally rich in detrital muscovite, interbedded with grey silty mudstones. Slumping, with soft-sedimentary attenuation of the sandstones, resulting in lenses, is widespread. A thick package of massively bedded quartzites, at least 30 m thick, occurs at [6738-95762]. There are also black hemipelagic mudstones.

From El Cisne, the metamorphic grade rises progressively westwards into metasedimentary rocks, still recognizable as turbidites, that were previously included within the Zambi Phyllites (Kennerley, 1973) and the El Tigre and La Victoria Units (Aspden et al., 1995). At [6693-95768] black mudstones are converted to graphitic phyllites with chiastolite (andalusite) porphyroblasts. Through rising metamorphic grade, the phyllites pass west into biotite schists.

There is also a decline in metamorphic grade approaching the Jubones Fault System. Exposures in the Río Jubones and the Machala-Cuenca road east of Pasaje, for example [6378-96322], display grey phyllites, slates (probably sub-greenschist facies), weakly cleaved conglomerates and psammites.

Small parts of the Cordillera Real have been remapped. The largest comprises the phyllites and flaggy psammites on the southeast side of the outcrop, north of Loja. These are faulted against, and locally thrust over, the Sacapalca Unit. These strata equate with the Chigüinda Unit (BGS and CODIGEM, 1993a) or Zamora Series (Kennerley, 1973).

Inliers of low-grade metamorphic rocks also occur within the volcanic outcrop (Figure 1). South of the Jubones Fault System, the principal inliers are Salvias, Cordoncillo, Río San Luis, Río Chinchilla and Manú. North of the fault, an inlier occurs at San Pablo de Cebadas. An unusual body of metamorphic rocks also occurs within the Bella Rica Basalts (Pallatanga Unit) immediately to the west of the Tenguelillo serpentinite [6606-96598] (Section 6). All the inliers are described in the details section below.

3.1.1 Interpretation

The El Oro metamorphic complex is considered to be mainly Paleozoic to Cretaceous, with metamorphic events in the Triassic and Cretaceous (Aspden et al., 1995). It is interpreted to be part of an accretionary prism, a conclusion supported by the intercalation of high-grade rocks (gneisses and blueschists) and low-grade phyllites, presumably the prism matrix. Similar juxtapositions of high- and low-grade are apparent at San Pablo de Cebadas and Manú. The westward extent of the metamorphic basement is uncertain.

A major dip-slip movement on the Jubones Fault System, probably north-verging and reverse, brought metamorphic rocks over the Saraguro Group. This explains the profound change in structural level from north to south. Evidence from the east end of the Jubones Fault System (Section 5), suggests that this happened about 10 Ma, at the same time as the inversion of the Ayancay Group intermontane basin.

The change in metamorphic grade west of El Cisne is similar to the profound change in metamorphic grade that occurs in the south of El Oro. North of Puyango, non-metamorphosed and weakly metamorphosed pre-Triassic sedimentary rocks (El Tigre Unit) pass northwards through andalusite and biotite isograds into the high-grade pelites of the La Victoria Unit (Aspden et al., 1995; Feininger, 1978). The non-metamorphosed rocks at El Cisne may therefore belong to the El Tigre Unit, however, the relationships around El Cisne, and farther south, are very poorly known.

The metamorphic rocks within the Bella Rica Basalts at Tenguelillo may be the products of localized shearing.

3.1.2 Details

3.1.2.1 Salvias*:* This 10 km-long inlier occurs between Salvias and Daule [6635-95972], northeast of Zaruma. It comprises phyllite, semi-psammite and chlorite schist, probably up to mid-greenschist grade because biotite is present in some places. A quarry [6604-95968] shows thinly interbedded buff psammites and grey chloritic semi-psammite/schist. There is a strong, sub-horizontal intersection lineation between the bedding and foliation. Exposures in the Río Salvias [6600-95960] also show a weakly foliated granodioritic gneiss (intrusive rock) with narrow (to 0.3 m) selvages of grey banded schist with quartz ribbons. The main mafic mineral in the gneiss is amphibole.

3.1.2.2 Quebrada Saladillo: Comprises psammites, semi-psammites and chlorite schists. These are well-exposed south of the Río Saladillo [6538-96070]. The foliation is steep and strikes east, the typical orientation in the El Oro metamorphic complex. River boulders in the Rio Saladillo [6543-96078] include fine, foliated amphibolite.

3.1.2.3 Río San Luis: This large inlier, about 7 km long, occurs northwest [6730-95929] of Gualel. It comprises graphitic phyllites, psammites and foliated granodiorite.

3.1.2.4 Quebrada Chinchilla: South of Laguna Chinchilla a small inlier [6763-95986] occurs along a north-northeast fault. It has been mapped only on the basis of psammite samples brought back by the stream sediment samplers.

3.1.2.5 Manú: This inlier comprises weakly foliated muscovite/biotite granodiorite, banded gneiss, biotite schists, psammites and graphitic phyllites. The best exposures, in the Río San Nicolás [6792-96145], are garnetiferous (almandine) gneisses. They are banded, on a centimetre scale, with qtz + musc and bt + qtz + feld bands. A fission track analysis revealed a range of single grain (zircon) ages between 31 and 130 Ma (Appendix 1). Graphitic black phyllites occur at [6789-96153], alongside banded gneiss exposures.

3.1.2.6 San Pablo de Cebadas: This large inlier of regional metamorphic rocks, about 7 km long and up to 4 km wide, probably links northwards with the Chaucha metamorphic rocks (Dunkley and Gaibor, 1997). All the exposures comprise metasedimentary rocks, including graphitic phyllites, muscovite schist, chloritic phyllite and psammite. In addition, large river boulders of coarse foliated bt + feld + qtz schist occur at [6698-96658]. On the west side the inlier is faulted against a wedge of the Bella Rica Basalts. On the east, it is overlain with strong angular unconformity by Saraguro Group acid tuffs. There is strong evidence, for example at Tutucachi [6715-96600], that both the metamorphic rocks and the overlying Saraguro tuffs were folded prior to deposition of the Jubones Tuff, during an intra-Saraguro deformation phase.

3.1.2.7 Tenguelillo: A body of metamorphic rocks occurs within the Bella Rica Basalts immediately to the west of the Tenguelillo serpentinite [6606-96598]. They are poorly exposed and mainly comprise a boulder field of coarse, variably foliated amphibolite-hbl gabbro, calc-schist and sheared granodiorite. The granodiorite displays annealed, granoblastic texture (WP-1652). The large quartz grains are strained and show grain size reduction at their margins. The rock is cut by narrow zones of actinolite. The original mafic minerals have been altered to chlorite and actinolite. The calc-schist comprises epidote, calcite and muscovite with some opaque ore (WP-1653B).

3.2 Pallatanga Unit (McCourt et al., 1997)

This unit comprises tectonic slices of ultrabasic rocks, basic oceanic volcanics, volcanoclastics and pelagic sediments exposed along the length of the cordillera. In the present area it is represented by massive, dark green, aphyric basalts with subordinate hyaloclastites, the **Bella Rica Basalts,** well exposed at [6441-96600], east of Ponce Enríquez, where there are numerous road and natural exposures as well as underground workings. Principal outcrops are between Ponce Enríquez (Bella Rica) and Tenguelillo, in the Río Jubones and in a faulted wedge west of San Pablo de Cebadas (see details section) (Figure 9). The base does not crop out and the unit is overlain unconformably by the Saraguro Group. The basalts have suffered mild hydrothermal alteration with chlorite, calcite, epidote and actinolite. They are so tough that they are commonly described as silicified in mining company reports. However, evidence of addition of silica is rare. Determination of bedding dip is only possible where hyaloclastite intercalations are present and even then, there is some uncertainty because of their irregular form.

Fine-grained intrusions are commonly difficult to distinguish from lava and hamper estimates of thickness. Dolerite ("diabase") and gabbro intrusions have distinctive, elongated, radially arranged feldspars. This variolitic texture is typical of both the lava and intrusions. The similarity in petrography suggests that the intrusions are contemporaneous with the lavas. Geochemically, the rocks are low-K (<0.25% K), tholeiitic basalts with ocean floor characteristics (Appendix 2). They plot in the basalt field of the SiO_2/Na_2O+K_2O diagram (Le Bas et al., 1986).

Serpentinites occur along some faults within the Bella Rica Basalts outcrop (Section 6).

3.2.1 Interpretation

Geochemically and petrographically the basalts and hyaloclastites are very similar to the Chanchán Basalts (Dunkley and Gaibor, 1997) and also resemble the Piñón Formation of the Costa (Feininger and Bristow, 1980; Le Brat et al., 1987; Tschopp, 1948). They were probably erupted in a submarine environment since they are intercalated with pillowed basalts. Their mild metamorphism is interpreted as submarine diastathermal type (cf. Aguirre, 1992). Basalts with ocean floor chemistry are known to form in marginal basins (Kokelaar and Howells, 1984), and a similar setting is possible for the Bella Rica Basalts.

3.2.2 Details

3.2.2.1 Bella Rica, Tres Ranchos: In this area the unit has a thickness of at least 1 km. Exposures at Bella Rica [6441-96600] and Tres Ranchos [6447-96588] are massive, extremely hard blue-green lavas, which locally have excellent pillows. The lavas are holocrystalline, variolitic, aphyric and strongly altered (e.g. WP-273, 448). The original mafic mineral (clinopyroxene?) has been altered to actinolite. There are numerous veinlets of epid + act + pyrite + albite + qtz + chl + calc. Hyaloclastite from Tres Ranchos shows angular, aphyric glass shards between 1 and 10 mm in length. There is a strong alteration to calc + chl + act + sphene (WP-452A). In general, the hyaloclastites have suffered greater alteration than the lavas. Geochemical samples from the Bella Rica access road comprise basalts and fine dolerites with strong propylitic alteration (WP-1666, 1667, 1668). The dolerite was probably sub-volcanic (high level) because it includes interstitial chloritized glass (WP-1666). It also displays a variolitic texture. The long thin plagioclases are strongly corroded. Some of the amphibole, which largely occupies spaces between the radial plagioclases, is primary hornblende, not an alteration product.

3.2.2.2 Río Gala, Tenguelillo: The second large outcrop is in the northeast corner of the Ponce Enríquez 1:50000 sheet [6590-96620], around the southern extension of the Chaucha batholith (Figure 9). They are poorly exposed, but large boulders litter the slopes. Fine dolerites and gabbros, with coarse variolitic texture are widespread. A thin section of one displays a sub-ophitic texture of fresh clinopyroxene and plagioclase, with only slight epidote and chlorite alteration (WP-1664). A large gabbro intrusion, also with propylitic alteration (WP-1670), is present on the north side [6486-96676] of the district. Over 20 m of massively bedded, very fine-, to medium-grained hyaloclastites (clasts 1-10 mm) and coarse basaltic breccias with abundant calcite veinlets are exposed in the Quebrada La Cachi [6566-96623].

3.2.2.3 The Tenguelillo hornfels: Immediately east of the Tenguelillo basalt outcrop, there is a narrow belt, 0.6 to 1 km wide, of strongly hornfelsed rocks of uncertain affinity. They comprise exceptionally tough, grey, white-stained, well-jointed rocks which commonly have a banded (bedding, flow banding?) appearance. A thin section of a grey banded rock [6618-96583] shows a hornfelsed fine sediment or tuff with sparse large quartz crystals and considerable white mica (in radial sprays) and stilpnomelane (WP-1649). The fine matrix is overprinted by inclusion-rich cordierite (?). Elsewhere [6617-96584], the hornfelsed belt includes undoubted fine, green quartz diorite, also hornfelsed. The hornfelsed rocks finish abruptly at [6620-96582], passing into typical Saraguro Group rocks.

3.2.2.4 West of San Pablo de Cebadas: A faulted wedge of the unit runs between San Pablo de Cebadas, at the north margin of the field area, and Narihuiña [6643-96553]. It comprises mainly massive variolitic basalts (WP-1646), with rare pillows.

3.2.2.5 Jubones Inlier: This is an east-west, tectonic inlier along the Jubones Fault System. Exposure, in the river bed, is excellent. Because of folding, no coherent sequence can be recognised. Pillow lavas are exposed in a few places, for example at Ducos [6425-96337], but massive, dark green, aphyric basalts dominate. They are sheared, brecciated and quartz-veined by movements on the Jubones Fault System, breaking along smooth, slickensided surfaces into small deeply weathered pieces. It is difficult to find fresh rock. Pillow lavas at [6425-96338] are intruded by a narrow dyke, ca. 3 m wide. The dyke is a fine diorite with abundant pale brown amphibole and a small amount of quartz (WP-158a). The feldspathic groundmass is largely altered to calcite, chlorite and sericite.

3.2.2.6 Serpentinites: Serpentinites occur along the east-southeast-striking, vertical Río Chico Fault. The fault can be traced between the Río Chico [6475-96688], near Shumiral, and San Gerardo (Figure 9). The rocks are strongly foliated, green and aphyric. The foliation is generally parallel to the fault. This survey has traced the bodies as far east as Tenguelillo, largely on the basis of loose boulders. Beyond that, within Saraguro tuffs, the serpentinites disappear and there are only faults with minor displacements. A foliated serpentinite, up to 600 m wide, crops out at Tenguelillo [6606-96598]. The margins, and the foliation, are vertical and strike northeast. It lies close to the inferred extension of the Río Chico Fault and is probably a serpentinite-filled complementary fault. The existence of other serpentinites is inferred by boulders in the northeast corner of the Ponce Enríquez 1:50000 sheet, in the Río San Miguel [6625-96663].

3.3 Celica Unit (new)

Volcanic rocks exposed between Laguna Sarihuiña [6809-95934] and El Cisne [6570-95745] and comprising deeply weathered andesitic-dacitic tuffs and andesitic to basaltic lavas are tentatively assigned to the Cretaceous “Celica Formation” (DGGM, 1973a) based on field relationships with the unconformably overlying early Tertiary Sacapalca Unit (section 3.6). In the type area of the Alamor basin some 50 km to the south of Zaruma, the Celica Unit is assigned an Albian age.

Similar lithologies in the Zaruma area previously assigned to the Celica and Piñón Formations are provisionally considered to belong to the Saraguro Group and described under the Portovelo Unit.

3.4 Yunguilla Unit (cf. Yunguilla Formation, Thalmann 1946)

Turbiditic sequences of Maastrichtian age, which have been assigned to the Yunguilla Unit occur along both the eastern and western margins of the map sheet.

In the east, flanking the western margins of the Cordillera Real, the main outcrops are at Cumbe and west of Selva Alegre (see details) (Figure 1). The Cumbe Inlier comprises over 1.5 km of strata. On its west side, the unit is apparently overlain by the Quingeo Formation. All other contacts are with the unconformably overlying Sacapalca Unit and/or Saraguro Group. The base does not crop out.

At Cumbe, road cuttings [7218-96581], about 1 km from the top of the sequence, display massive (non-bedded) medium grey, sandy mudstones with numerous *Diplocraterion* (U-shaped) burrows infilled by sandstone. The tubes are 5-8 mm in diameter and cut across bedding. Other, meandering sandstone-filled tubes, up to 15 mm in diameter, follow bedding and resemble *Thalassanoides*. Small shelly and phosphatic fossils are widespread. A microfossil assemblage (WP-347a, b) from the locality indicates a Campanian-Maastrichtian (Late Cretaceous) age (Petroproducción, 1996). The rich fauna includes benthonic and planktonic foraminifera, calcareous nannofossils and radiolarians. Macrofossils from the same locality include poorly preserved ammonites of the genera *Baculites* and *Hoploscaphites*, confirming the same age range (Woods, 1997). A heavy mineral analysis of a Yunguilla sandstone from here comprises zircon 34% (well rounded), monazite 6%, tourmaline 21%, rutile 5%, titanite 4%, cassiterite 1.5%, apatite 20%, garnet 20% and epidote 1.5% (pers. comm., Wilfred Winkler, April, 1997).

In the west of the mapped area, turbiditic sediments are found associated with the Bella Rica Basalts of the Pallatanga Unit. They are exposed along the Río Jubones and in the Bella Rica area and assigned to the Yunguilla Unit on palaeontological and lithological evidence (see detail).

3.4.1 Interpretation

The unit is marine and dominantly turbiditic. There are no bedforms of above storm wavebase conditions in the disturbed upper 1 km, although this may reflect destruction by burrowing. There was a mixed metamorphic and volcanic source. The very limited palaeocurrent data suggest a west source, perhaps the El Oro block. The burrowed upper part suggests shallower, perhaps mid-shelf conditions. Dr. Winkler interprets the well-rounded zircons as indicating a partly secondary sedimentary cycle, that is, they are partly derived from pre-existing sedimentary or metasedimentary rocks.

3.4.2 Details

3.4.2.1 Cumbe: These strata are mainly turbidites, with normal grading and Bouma sequences of bedforms (T_{a-c}). Beds are commonly 0.15-0.3 m thick, with intervening dark grey mudstones, planar-laminated of 20-40 mm thickness. Compositionally, the coarser sandstones comprise quartz and feldspar grains with common small cherty black mudstone lithic fragments. The ratio of sandstone to mudstone is variable, in some places the sandstones reach only a few centimetres in thickness and account for less than 10% of the sequence. Septarian silica concretions are widespread. Fine conglomerates occur at San Francisco [7218-96570]. Exposure is poor, but they are probably thick (>1 m) beds. Pebbles are mainly vein quartz, psammite, schists and sandstone.

Trace fossils, mainly horizontal meandering traces, are common on sandstone bases. Cross-cutting bioturbation is mainly absent, but there are thin sequences in which bedding becomes poorly defined and bioturbation intense. Palaeocurrent data, entirely from ripple cross-stratification, were collected from [7220-96578]. Palaeocurrents were towards 038°, 128°, 078°, 037° and 155°, mainly towards an east vector.

3.4.2.2 Selva Alegre to Manú: This is a block of strongly folded, vertical to overturned turbidites. It is constrained to the east by the Girón Fault System. The western boundary is concealed beneath the Saraguro Group, but it probably overlies the Manú metamorphic rocks. The best exposures occur between [6807-96077] and [6822-96085]. Slumping and boudinage are widespread, giving the appearance of a sedimentary mélange (Plate 1a). The rocks are very similar to Cumbe, that is, indurated conglomerates (almost entirely of rhyolite or cherty mudstone clasts), fine to coarse sandstones and chert mudstone interbeds. Most sandstones are quartzose, but the only sectioned sample is rich in fragments of andesite and rhyolite and large plagioclase crystals (WP-595). At [6820-96085], overturned sandstones and cherty mudstones include a 0.5 m thick, soft black, carbonaceous mudstone. Samples for micropalaeontological analysis were barren. Ripple cross-stratification from the sandstones gives palaeflow towards 070°.

3.4.2.3 Bella Rica area: Sandstones, siltstones and mudstones, at least 200 m thick, which crop out in the Quebrada Florida [6438-96578] were described as "metaquartzites interbedded with muscovite and biotite phyllites" by the Belgian Mission (Misión Belga, 1996). However, they show little or no metamorphism. Dips are moderate to steep northeast and the contact with the basalts is probably faulted (Río Margarita Fault). The strata are very similar to the ammonite-bearing rocks of the Río Jubones. They comprise either thinly interbedded, turbiditic fine to medium sandstone and silty mudstone or a distinctive, dark grey massive, non-bedded fine sandstone with large detrital muscovites. Most of the rocks are calcareous, suggesting the presence of calcareous microfossils. A micropalaeontological analysis indicates a late Cretaceous probably Maastrichtian age (Wilkinson, 1997).

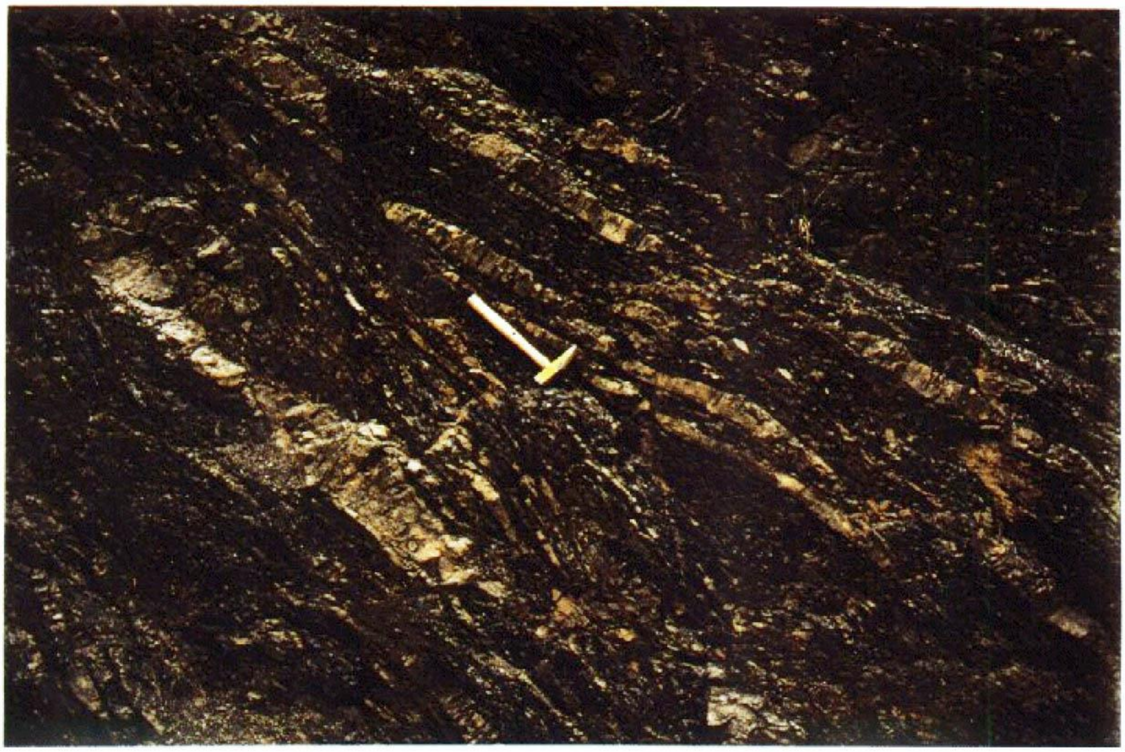

Plate 1a. Yunguilla Unit. Typical disturbed, boudinaged turbiditic sandstones and silty mudstones. Road section [6807-96077] between Manú and Selva Alegre

Plate 1b. Argillic alteration in rhyolite or altered andesite? Zaruma [6536-95925]. Abundant disseminated pyrite gives sulphurous yellow weathering colours

3.4.2.4 Río Jubones-Ducos area: A distinctive sandstone occurs in the Jubones Inlier. It is rusty weathered, dark grey when fresh, and completely massive. Exposures at Ducos [6414-96342] indicate a substantial thickness (> 100 m). In thin section, a fine sandstone [6397-96330] comprises angular quartz grains of equal size, sericitised feldspar, muscovite, biotite flakes (folded by compaction), opaque ore, foraminifera and possible ostracods (WP-178). A large ammonite was found in this sandstone near Ducos [6414-96342]. It is possibly of the *Perisphinctaceae* superfamily (Woods, 1997). Other sedimentary rocks occur in the Jubones window. At Calayucu [6463-96337] river exposures are of thinly interbedded black cherty mudstones and pale brown, cherty fine sandstones and siltstones. They are distal turbidites. Some display miniature dewatering structures, such as sand volcanoes. Only 200 m upstream are exposures of a spectacular conglomerate, about 50 m thick. It comprises tightly packed angular cobbles and boulders, up to 0.4 m, of jasper, black chert, basalt, fresh obsidian and fine dolerite. The latter has the typical variolitic texture of the Bella Rica Basalts. The matrix is chert red mudstone. Vague, very massive beds are defined by changes in clast size.

East of Ducos [6437-96337], there are large exposures of massively bedded coarse sandstones, probably proximal turbidites. Individual beds are approximately 3 m thick and graded from fine conglomerate to fine sandstone. Dune cross-stratification in the sandstones gives palaeocurrent flow towards 288°. Vein quartz and feldspar are the dominant components. Fine sandstones and rare pale brown cherty mudstones intervene between the coarse sandstones.

3.5 Quingeo Formation (Hungerbühler and Steinmann, 1996; Steinmann, in prep.)

This is defined as red/purple sandstones, siltstones, conglomerates and mudstones. It crops out mainly to the north of the field area, around Quingeo [7335-96715], where it is at least 1.2 km thick. There, the base is not exposed and the Yunguilla Unit is thrust over the formation. The top is marked by the unconformably overlying Saraguro Group.

Purple sedimentary rocks above the Yunguilla at Cumbe, 10 km directly along strike from Quingeo, were previously included within the Saraguro Group (Figure 1; DGGM, 1974). Because of the lithological similarity with the type area, we correlate them with the Quingeo Formation.

At Cumbe, the base is put where turbidites disappear, vertical bioturbation becomes intense and there is a colour change from the greys of the Yunguilla Unit to yellow-stained purple sandstones and silty mudstones. The bulk of the formation comprises massive, poorly bedded silty mudstones, siltstones and fine sandstones. Simple tubular, sandstone-filled burrows cut across bedding at variable angle and reach 10 mm in diameter and 80 mm in length. U-shaped burrows also occur. Carbonate is widespread, in veins and calcareous mudstones. There are also scattered thick (up to 4 m) bodies of yellowish, rotten fine sandstone, for example [7206-96587]. They seem to have planar lamination, but bioturbation may have overprinted large scale cross-stratification. Small calcareous nodules are common.

About 100 m above the base of the formation, on the Panamerican highway [7212-96589], ochreous mudstones with ill-defined bedding and shell-packed sandstones and muddy limestones yield abundant moderately well-preserved gastropods and bivalves (all articulated) (Woods, 1997). The most abundant fossil is *Pterotrigonia*, a thick-shelled bivalve which is known from Maastrichtian beds in northern Perú. The palaeoecology appears to reflect an in situ 'life' assemblage, or an assemblage that was transported only a very short distance. Some of the intense burrowing in the Quingeo may reflect the activities of gastropods and bivalves. In its type area, fission track dates indicate a minimum age of Middle Eocene and an upper age of Early Oligocene (Hungerbühler and Steinmann, 1996). The fossils from Cumbe are Maastrichtian (latest Cretaceous).

3.5.1 Interpretation

The formation at Cumbe is probably a shallow marine to terrestrial (deltaic to fluvial) sequence. The reddening, caused by an influx of hematite, indicates the presence of nearby subaerial weathering, probably in an arid or tropical environment. The Quingeo Formation of the type area is considered to be mainly fluvial, with a metamorphic input (Hungerbühler and Steinmann, 1996). It is possible that the lower, marine-influenced, part (that exposed at Cumbe), is absent, hidden beneath the overthrust Yunguilla Unit.

There are no outcrops of the formation south of Cumbe, but there are poorly dated red-beds above Cretaceous turbidite sequences in Perú and Bolivia with which it may correlate (Jaillard et al., 1993). Northwards, the sequence may correlate with the Silante Unit of the Western Cordillera, which overlies the Yunguilla Unit west of Quito (Hughes and Bermúdez, 1997). Eastwards, in the Oriente, black mudstones and limestones (Napo Formation), with an upper age of Early Campanian (Bristow and Hoffstetter, 1977), are overlain disconformably by the Maastrichtian Tena Formation red-beds. Baldock (1982) notes that thin sandstones of possible Campanian or Maastrichtian age intervene between the Napo and Tena Formations and may represent a true transition. The incoming of Maastrichtian red-beds is interpreted as the same shallowing event represented by the Yunguilla-Quingeo transition.

The Quingeo was probably partly contemporaneous with the Sacapalca Andesites and Saraguro Group. It accumulated closer to the metamorphic hinterland of the Cordillera Real and farther away from the axis of the Sacapalca arc.

3.6 Sacapalca Unit (new)

It comprises a sequence of andesitic volcanic rocks, with tuffaceous sedimentary rocks (red mudstones, sandstones and conglomerates) and sparse dacitic/rhyolitic tuffs. It overlies the Celica Unit and is overlain by the Gonzanamá Formation to the south of the mapped area. This definition is the same as the original lithostratigraphic definition of the "Sacapalca Formation" (Kennerley, 1973; Bristow and Hoffstetter, 1977), however, it is here redefined as an informal unit.

The main outcrop is between the Cordillera Real, Catamayo and El Cisne, where it occupies the major north-striking Chuquiribamba Syncline (Figure 1). The outcrop is constrained in the east by a north-striking reverse, to normal, fault (Catamayo Fault), that brings up graphitic phyllites and flaggy psammites. The west side of the outcrop is ill-defined because of fault complications at El Cisne, granodiorite intrusions and hornfelsing. An estimate of the minimum thickness, about 3 km, is possible west of Santiago.

The unit has a much greater extent than was envisaged. Kennerley (1973) considered that the Catamayo-Chuquiribamba outcrop was the fill of a north-south graben which was terminated near Santiago [6890-95800] (DGGM, 1975a). However, there is a huge thickness (> 2 km) of the Sacapalca just south of Fierro Urcu [6837-95887] and it is unlikely, given the structural geometry, that this disappears. Furthermore, the same lithologies are mappable between Santiago and Saraguro and descending the north flank of Fierro Urcu. The andesitic sequence can also be traced without interruption to the Río León and La Cría. Therefore, a large part of what was formerly mapped as the Saraguro Group, is now assigned to the Sacapalca Unit (see details).

The strata are mainly reddish, purple and green massive andesites, andesitic debrites (Plate 2b), conglomerates and sparse acid tuffs. Irregular carbonate veins are common. In areas of sedimentary interbeds, the outcrop is strongly featured. Petrographically, the andesites of the Sacapalca Unit are fresher than those of the Celica Unit. Flow foliations are well preserved and fresh glass survives in some (WP-881, 893). A very fresh sample from near Catamayo is flow-foliated, with augite and plagioclase phenocrysts (WP-824). There is a widespread chlorite and calcite alteration, but, by comparison with the Celica, epidote is largely absent. This is a useful field tool for distinguishing the two units.

The base of the unit steps down onto progressively older rocks towards the east. At El Cisne, and farther north, it sits on the andesites of the Celica Unit. Eastwards, it overlies metamorphic rocks at Catamayo and east of Fierro Urcu.

At Catamayo the unit includes undoubted Palaeocene-Early Eocene or older strata (Jaillard et al., 1996), because it is intruded by the San Lucas pluton (59-51 Ma; Aspden et al., 1992) and by the El Tingo intrusion (47 ± 2 Ma K/Ar, hornblende; 50 ± 3 Ma K/Ar, biotite; Kennerley, 1980). A new fission track age of 66.9 ± 5.8 Ma from the base of the unit near Catacocha (DH-385, Appendix 1) also implies latest Maastrichtian or early Palaeocene (Hungerbühler, in prep). The beds overlie the Campanian to Maastrichtian Casanga Formation (Jaillard et al., 1996).

The Gonzanamá Formation, which overlies the unit to the south at Gonzanamá, was thought to be Maastrichtian or Palaeocene (Bristow and Hoffstetter, 1977; Kennerley, 1973, 1980; DGGM, 1975b). However, three new fission track dates (DH-394, 439 and 443), between Nambacola and Gonzanamá demonstrate a Middle Miocene age (Hungerbühler, in prep; Appendix 1). Ostracods also show similarities to other Middle Miocene faunas in the Tertiary basins of Ecuador. Therefore, the Sacapalca Unit is clearly pre-Middle Miocene. Red-beds that unconformably overlie the unit at Catamayo were correlated with the Gonzanamá Formation (DGGM, 1975b, a). However, they are also probably mid-Miocene (pres. comm., Hungerbühler, April 1997) and are referred to as the Catamayo Formation (Jaillard et al., 1996).

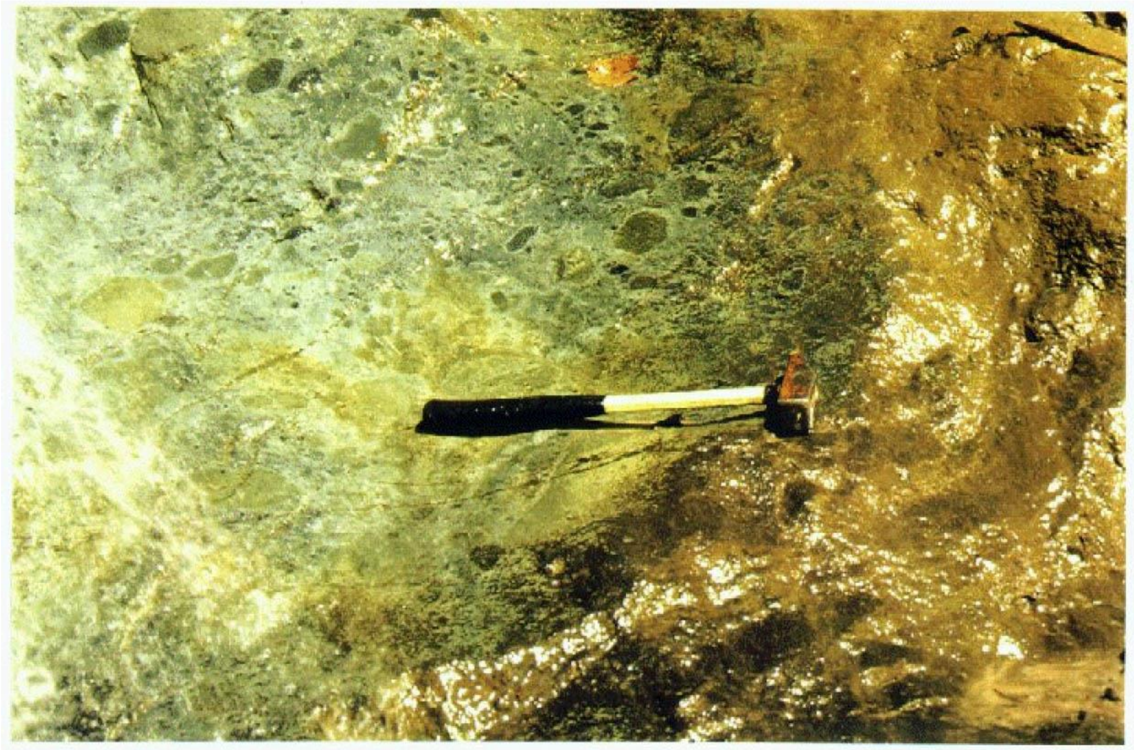

Plate 2a. Green, epidotic lapilli-tuff exposed in gold mine northeast of Zaruma, Portovelo Unit [6544-95925]

Plate 2b. Andesitic debrites, north of Catamayo and west of Taquil. Sacapalca Unit [6899-95696]

At the north end of the outcrop, andesites in the road [6828-96202] between Manú and the Mina de Mármol, close to the base of the overlying Saraguro Group, yield a Late Oligocene age by the fission track method (24.8 ± 0.8 Ma) (Appendix 1). This may reflect resetting by heating beside an intrusion. However, it is possible that andesites within the Saraguro Group have been confused with the Sacapalca Unit.

3.6.1 Interpretation

The unit probably represents interfering terrestrial andesite volcanoes and associated outwash debris. The combination of bright colours and REDOX features, such as green spots and bleached joint surfaces, supports a terrestrial environment. The abundance of calcite may reflect circulation of bicarbonate meteoric waters. Temporary lakes were developed at times. There is also little evidence of input from a metamorphic source, suggesting that the Cordillera Real was subdued or concealed by volcanic rocks. There is no strong evidence for a tectonic graben north of Catamayo (Kennerley, 1973). No obvious lateral facies changes occur towards the Catamayo Fault, for example.

If the fission track date of 24 Ma is correct and has been correctly attributed, the age evidence suggests that large time spans are not represented. Unfortunately, regional disconformities cannot be recognized because of the monotony of the sequence. Future work may demonstrate the existence of two sequences separated by a disconformity, a lower one of Palaeocene-Early Eocene(?), and an upper one of Late Oligocene age. The Lage Oligocene fission track date suggests that the Saraguro Group and the upper part of the Sacapalca Unit interdigitate. The Saraguro ash-flow tuffs may not have been deposited in the south, perhaps because of a southward change from an ash-flow-dominated province (Saraguro Group) to an andesite-dominated province (Sacapalca Unit). Alternatively, major unconformities may cut them out in the south. The few thin dacitic ash-flow tuffs, for example, those in the Chuquiribamba Syncline, may be distal representatives of the Saraguro Group.

Available whole rock geochemical data and the abundance of plagioclase and clinopyroxene/amphibole-phyric andesites imply a calc-alkaline (arc) composition. The arc was constructed on continental crust (the El Oro metamorphic complex). Part of the Sacapalca Unit may be contemporaneous with the volcanoclastic Palaeocene-Early Eocene Macuchi Unit of the Western Cordillera farther north (Hughes and Bermúdez, 1997).

3.6.2 Details

3.6.2.1 Catamayo-Chuquiribamba: This mainly andesitic outcrop includes at least three, thin (< 30 m) acid ash-flow tuffs. Near Taquil [6896-95693], the lowest, a rubbly weathered buff welded tuff has possible pumice and scattered large quartz and feldspar crystals. At Gonzabal [6865-95685] a 10-15 m thick welded tuff has common pumice, quartz and biotite. The stratigraphically highest acid tuff [6858-95698] is very similar. A concordant rhyolite, about 60 m thick, occurs west of Gonzabal [6860-95690]. It is probably a sill.

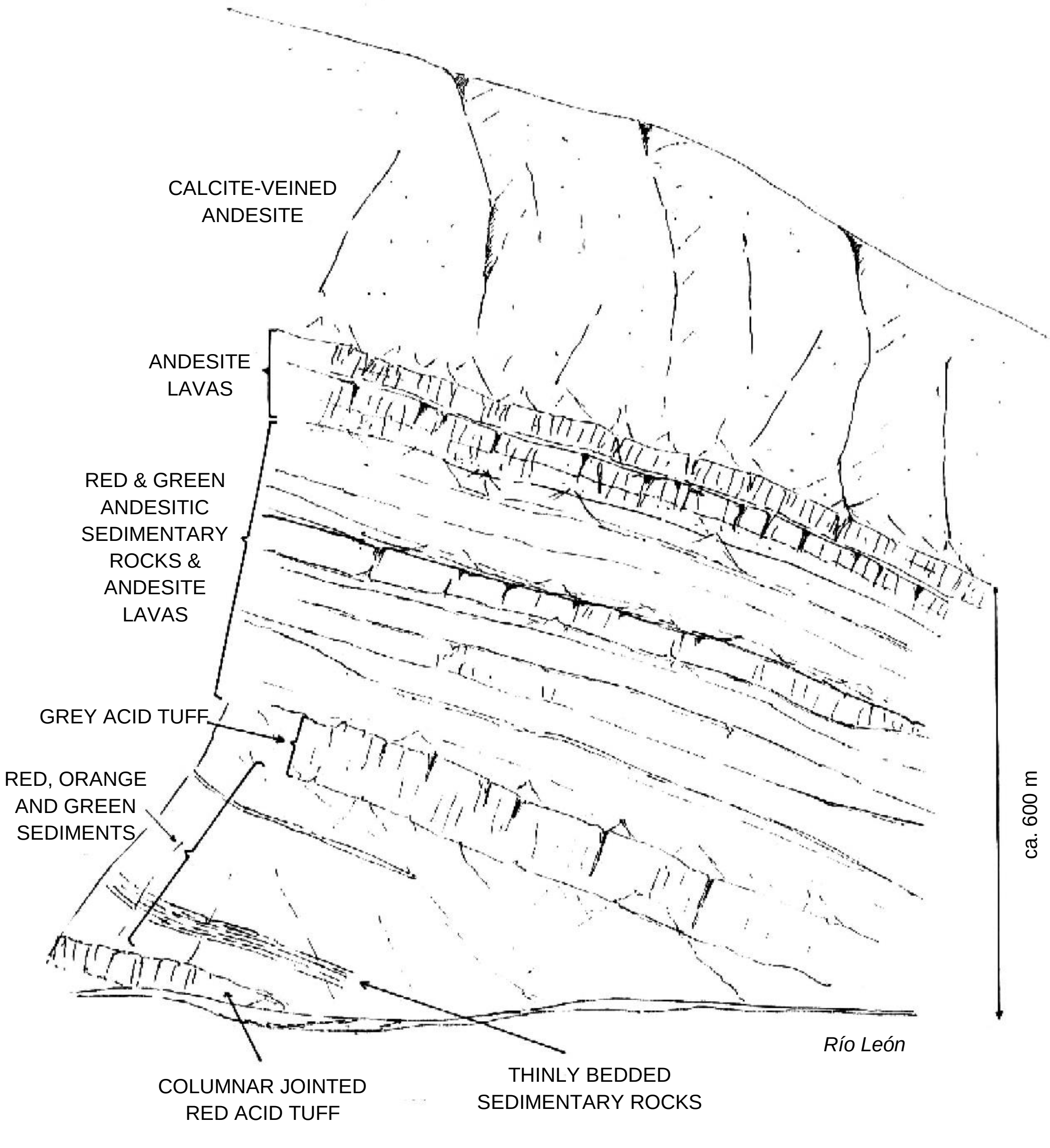

Figure 3. Sacapalca Unit. Sketch of Filo de Seucer [6880-96195], viewed from east

3.6.2.2 Fierro Urcu: From Fierro Urcu to Gualel [6807-95835] a well-featured, > 2 km sequence is exposed on the east limb of the Chuquiribamba Syncline. Between [6848-95888] and [6835-95888] well-jointed, dark green/grey porphyritic andesite lavas are intercalated with red mudstones, strongly weathered andesitic lapilli-tuffs, andesitic conglomerates and pumice tuffs. In thin section, the andesites are very fresh, amphibole and plagioclase-phyric, with an excellent flow foliation (WP-665). The sequence culminates, at the faulted core of the syncline, in a rotten-weathered acid tuff, with scattered quartz and feldspar crystals and sparse pumices. Exposed on Loma Bernabé [6823-95875], it is about 200 m thick.

3.6.2.3 Fierro Urcu to San Pablo de Tenta: Between Fierro Urcu and the Panamerican highway there is a large outcrop. The Río El Llacu exposes andesitic tuff breccias, tuffaceous sandstones, conglomerates and sparse pumice tuffs. There are no acid tuffs. The components are identical to those south of Fierro Urcu. This is a critical area for demonstrating that the same sequence on the south side of Fierro Urcu continues on the north. Some of the highest exposed strata of the unit occur by the Saraguro-Selva Alegre road bridge [6898-95999]. They are 15 m of massive- to medium-bedded, coarse- to fine volcanic sandstones. They are ill-sorted and immature, dominated by andesitic material and poor in quartz. About 80 m above is the base of the Saraguro Group.

3.6.2.4 Santiago to Saraguro: The unit is widely exposed on the Panamerican highway between these places and farther south. Between 3 and 4 km south of Santiago, close to the base, there are rotten purple andesites [6899-95782] with intercalations of sedimentary rocks. At [6893-95777], 15 m of very finely bedded, lacustrine mudstones, locally with accretionary lapilli, overlie 15 m of pumice tuffs. Ill-sorted tuffaceous conglomerates and sandstones occur at [6897-95762].

Massive andesite lavas and andesitic tuff breccias dominate immediately north of Santiago. However, the sequence still includes sedimentary rocks: at [6916-95812] andesite lava or tuff is overlain by 3 m of thinly-bedded tuffaceous sandstone, sandy mudstone and red mudstone. A few kilometres northeast of Santiago, the San Lucas granodiorite intrudes andesite lavas. These rocks are probably the oldest part of the Sacapalca Unit in the field area. They form major, well-featured crags above the highway and are clearly visible in aerial photographs. The lava at [6936-95832] is flow-foliated and moderately altered; plagioclase phenocrysts have been altered to calc + epid, mafic minerals to chl + epid + calc (WP-733). Nearby, a pyrite-rich chloritic andesite, with flow foliation and sparse feldspar and amphibole phenocrysts, displays chlorite-filled vesicles. The more intense alteration on this stretch of road may reflect the influence of the intrusion. It is also possible that this is a narrow belt, a few hundred metres wide, of the Celica Unit.

Near San Lucas [6916-95860] graphitic phyllites are overlain by andesites with angular unconformity. Deeply weathered andesite tuff-breccias at the Fierro Urcu access road [6923-95933] also overlie graphitic phyllites. The contact is a west-verging thrust, but, given the strong contrast in strength between the rock types, it may be simply an unconformity with slight faulting.

3.6.2.5 Saraguro: The sequence is well-exposed on the Panamerican highway between Saraguro and Paquishapa (formerly Urdaneta). The lowest part is a 20 m thick basaltic andesite, exposed at [6987-96003]. It is a superbly fresh, flinty rock with a good flow foliation and columnar joints. Agate/chalcedony vugs are common. Plagioclase and augite phenocrysts occur in the fresh glass matrix (WP-510). It is overlain by about 120 m of well-bedded, quartz-rich tuffaceous sandstones, siltstones and silty mudstones. Thinly bedded tuffaceous sandstones dominate. A prominent 6 m sequence of flaggy, planar laminated fine feldspathic sandstone is well-exposed in the road [6987-96007]and forms a strong feature in the otherwise soft sequence on the surrounding hills. There are also a few massively bedded andesitic debrites.

From [6981-96017], the remaining 130 m of the unit comprise lavas, rubbly weathered, ill-sorted debrites and conglomerates. The debrite material is mainly andesitic, with a few clasts of pumice and acid tuff. Exposures at [6991-96023] comprise 15 m of debrites overlying purple/green andesite lava with common agate pockets. There are also a few thin (< 20 m), very fresh lava flows similar to those at the base. A thin section of one [7010-96017] is an andesite with a flow foliation of plagioclase and much interstitial augite and magnetite (WP-506). It has rare quartz phenocrysts.

The top of the unit is at [6978-96035], where a pink welded rhyolitic tuff overlies the andesitic debrites. This is the base of the Saraguro Group.

3.6.2.6 Río León: The best exposures of the unit occur in the Río León, at the union with the Río Naranjo [6915-96160]. There, superb three-dimensional exposure demonstrates a major north-northeast striking syncline [6924-96170] within the Sacapalca truncated by Saraguro rhyolitic tuffs (including the Jubones Formation). On the west side of the Río León, a single rockface [6880-96195], over 1000 m high exposes approximately 700 m of red and green andesites with a few acid tuffs (Figure 3). The reddened portions are the oxidised tops of lava flows. Foot traverses across the Río León have established a sequence of carbonate-veined, olive green andesites, andesitic debrites, sandstones and sparse dacitic welded tuffs. One such tuff can be matched up from the west, to the east, side of the Río León. It occurs in the truncated syncline, and opposite, above La Unión [6982-96161]. Additional exposures [6905-96118], easily accessible on a new road to Chuba, comprise andesitic tuff breccias/debrites with sparse red mudstones, thin andesite dykes, aligned 033/90, and planar bedded coarse tuffaceous sandstones.

3.6.2.7 Río Manú: Downstream of Manú, at the Río Manú and Río Uchucay junction [6814-96227], are extensive exposures of carbonate-veined, green andesites and andesitic tuffs. There is no direct link with the Río León outcrops, because of thrusts. However, the rocks are so similar that they are considered as Sacapalca. The andesites, gently west-dipping, are thrust eastwards over the vertical, to overturned, Jubones Formation and Ayancay Group (Plate 9a).

3.6.2.8 Girón: This inlier is the most northerly outcrop. It is juxtaposed against the Ayancay Group by the Girón Fault and is covered to the south, with strong angular unconformity, by the flat-lying La Paz Formation. It comprises rubbly andesites and andesitic debrites, rich in agate/chalcedony pockets and veins, and volcanoclastic sedimentary rocks. Excellent exposures of chalcedonic, poorly bedded andesitic debrites and andesites occur at Filo de Masta [7086-96525]. The rocks are very rusty and weathered. Pale grey and pale green quartzose sandstones and fine conglomerates are exposed east of Girón [7081-96506], beside andesitic debrites and andesites. Ill-defined, large-scale trough cross-stratification and channels give palaeoflow towards 240°. Clasts in the conglomerate are largely silicic tuffs and quartz crystal-rich tuffs with a little andesitic debris. The sequence, about 20 m thick, overlies 15 m of crudely bedded cream tuffs.

3.6.2.9 Cumbe: Andesitic tuff-breccias with agates occur near Cumbe at [7200-96513]. Andesitic debrites at [7199-96531] are interbedded with thin red mudstones. At El Arrayán [7177-96573] there are exposures of andesite with bright green chlorite amygdales, apparently beneath Saraguro acid tuffs and immediately above the Quingeo Formation. All three areas of outcrop are interpreted as windows of the Sacapalca Unit.

3.7 Catamayo Formation (Jaillard et al., 1996)

This Formation, previously included within the Gonzanamá Formation, comprises red, cream and green tuffaceous mudstones, siltstones and sandstones. The age relationships with the Sacapalca Unit are uncertain. It appears to overlie the unit with angular unconformity at Catamayo. However, the Catamayo area is complex structurally, with clear evidence of thrusting. On the Loja-Catamayo road [6857-96597], less than 4 km east of Catamayo, graphitic phyllites are thrust westwards over vertical Sacapalca andesites, about 35 m thick, and a packet of vertical debrites, mudstones, bright green tuffaceous sandstones, 70 m thick, that may be the Catamayo Formation.

3.8 Saraguro Group (DGGM, 1982; Baldock, 1982)

The “Saraguro Formation” and “Chinchillo Formation” (Kennerley, 1973; DGGM, 1973b) are here included under the Saraguro Group. This comprises andesitic to rhyolitic tuffs and lavas with subordinate sedimentary rocks. Because of its historical importance, however, the name “Saraguro” is retained, even though the type area for the group is not around Saraguro. Five discrete Formations (Las Trancas, Plancharumi, La Fortuna, Jubones and La Paz) and an informal andesitic sequence, the Portovelo Unit are recognized within the field area, but the majority of the mapped outcrop comprises undivided Saraguro Group.

The Group occupies most of the field area (Figure 1). The outcrop is larger than depicted on the previous 1:100000 maps and includes areas mapped before as the Tarqui Formation, such as the páramo north of Pucará and around Oña and La Paz. A large outcrop, previously mapped as Celica (DGGM, 1980a), is also recognized between Zaruma and Piñas. Furthermore, there is no logical reason for creating a new stratigraphic unit for the strata which cap the high páramo above Chilla, Manú and Selva Alegre. Consequently, these strata that were previously included in the Chinchillo Formation (DGGM, 1973b) are now considered to belong to the Saraguro Group.

The Group is largely flat-lying or only gently undulating (Plate 5b). Simplistically, there is a gradual decline in dips towards the páramo, in younger rocks. There are exceptions however, thus pre-Jubones Formation deformation along faults created belts of steep strata, for example at Pedernales, Narihuiña and San Pablo de Cebada.

The main lithology is tuff. Texturally, these vary from coarse tuff-breccia (Plate 3a) to crystal tuff (Plate 3b). The tuffs plot mainly in the rhyolite to dacite fields of the $SiO_2/Na_2O + K_2O$ diagram (Le Bas et al., 1986; Appendix 2). Some, like those of the La Fortuna and Jubones Formations, are very acid, with greater than 77% SiO_2 wt%. The 6 whole rock geochemical analyses correspond well with compositions estimated from field criteria.

These criteria are that:

a) Andesitic tuffs are green, with abundant plagioclase, amphibole and augite crystals. Vitroclastic textures are rare and welding foliations are less well developed.

b) Dacitic tuffs contain feldspar crystals (± amphiboles), some quartz crystals and have a pale green, pink or brown matrix. Welding textures and chloritized pumice lapilli are common.

c) Rhyolitic tuffs are white, pale brown or pink. Welding foliations are pronounced in outcrop, but vitroclasts are commonly destroyed by recrystallization and devitrification. Crystal content is very variable; feldspar and quartz are common. Biotite is an important component of some tuffs.

The thickness of the group is variable. There are some areas, such as the Río León, where it is only 1 km thick. There are others, such as the type area which amounts to 3 km. It is considered that the most complete sequences occur only north of the Girón and Jubones fault systems. The most complete section occurs between Narihuiña [6640-96543], where the Group sits on the Bella Rica Basalts of the Cretaceous Pallatanga Unit, and the páramo north of Quinuas [6654-96512], near Pucará (Table 1). It comprises a sequence of ash-flow tuffs with at least one major angular unconformity.

Sedimentary rocks are sparse in the type section but around the west and northwest fringe of the Ayancay Group outcrop they are well-developed (Santa Isabel “proto-basin”; Section 3.8.6). West of the Chaucha-Río Jérez Lineament, the Group also includes sedimentary rocks (Las Trancas Formation) (Table 2).

There is a wide spread of fission track and K/Ar age dates for the Saraguro Group. The oldest come from north of the field area. East of La Troncal [7164-97428], acid tuffs near the base gave 38.6 ± 1.3 Ma (the boundary between Middle and Late Eocene) (Dunkley and Gaibor, 1997). Farther northeast [6997-97252], a tuff at the base gave 37.0 ± 1.5 Ma. These tuffs probably correlate with lithologies beneath the Las Trancas Formation (Table 2). The highest formation within the field area, the La Paz Tuff, gives an age of 22.5 ± 0.9 Ma (earliest Miocene) (Appendix 1).

Table 1. Saraguro Group northwest of Quinuas

0.2	km	SANTA ISABEL FORMATION: Andesitic tuff-breccia. 18.4 ± 0.8 Ma (early Miocene) (Hungerbühler, in prep.).
		Tectonism and angular unconformity
0-0.4	km	JUBONES FORMATION: 22.76 ± 0.97 Ma (earliest Miocene).
0.6	km	LA FORTUNA FORMATION: 23.2 ± 0.8 Ma (earliest Miocene). The Formation wedges out to the northeast.
		Tectonism and angular unconformity
2	km	*The Narihuiña and Pedernales tuffs:* Sequence established between Narihuiña [6642-96536] and Quinuas [6654-96515]. Also, widespread exposure between Hornillos [6760-96570] and Pedernales [6825-96576]. Distinctive pink, brown, pale green welded tuffs. Strong eutaxitic fabrics. Pumice fiamme are common and there are variable proportions of quartz, plagioclase and amphibole crystals. The tuffs form relatively thin (< 100 m) units. A tuff at [6619-96509] was dated at 27.7 ± 1.0 Ma (Appendix 1). At Pedernales [6835-96603], sub-vertical tuffs, with the same textures, are exposed in an erosional window beneath the flat-lying Jubones Formation.
		Tectonism and angular unconformity
0-1	km	BELLA RICA BASALTS: Sequence established northeast of Narihuiña [6643-96553]. Massive, locally pillowed basalts.

Table 2. Saraguro Group west of the Chaucha-Río Jérez Lineament

		Chaucha-Río Jérez Lineament
1	km	LAS TRANCAS FORMATION: Dacitic to rhyolitic tuffs, tuff-breccias, conglomerates and sandstones rich in metamorphic and andesitic/dacitic debris. Type locality at Las Trancas [6586-96516].
1.75	km	Sequence established between Tendalitos [6570-96587] and Tenguelillo [6603-96609]. Comprises white/pink/pale brown, dacitic to rhyolitic welded ash-flow tuffs (variable quartz/plagioclase/amphibole crystal content, scattered pumices) and green crystal-rich (plagioclase/amphibole) andesitic/dacitic tuffs which are non-welded or very weakly welded. Thin red/purple mudstones also occur. Intercalations of thin pale- to dark-grey cherty turbiditic mudstones and siltstones occur near the base.
		Tectonism and angular unconformity
0.4 (?)	km	Hornfelsed rocks included in BELLA RICA BASALTS. [6556-96593] and [6618-96583].
1	km	BELLA RICA BASALTS: Basalts, locally pillowed. [6603-96608]

Plate 3a. Pyroclastic breccia, rich in pumice, obsidian and acid tuff blocks. Saraguro Group. Uzhcurrumi [6573-96328]

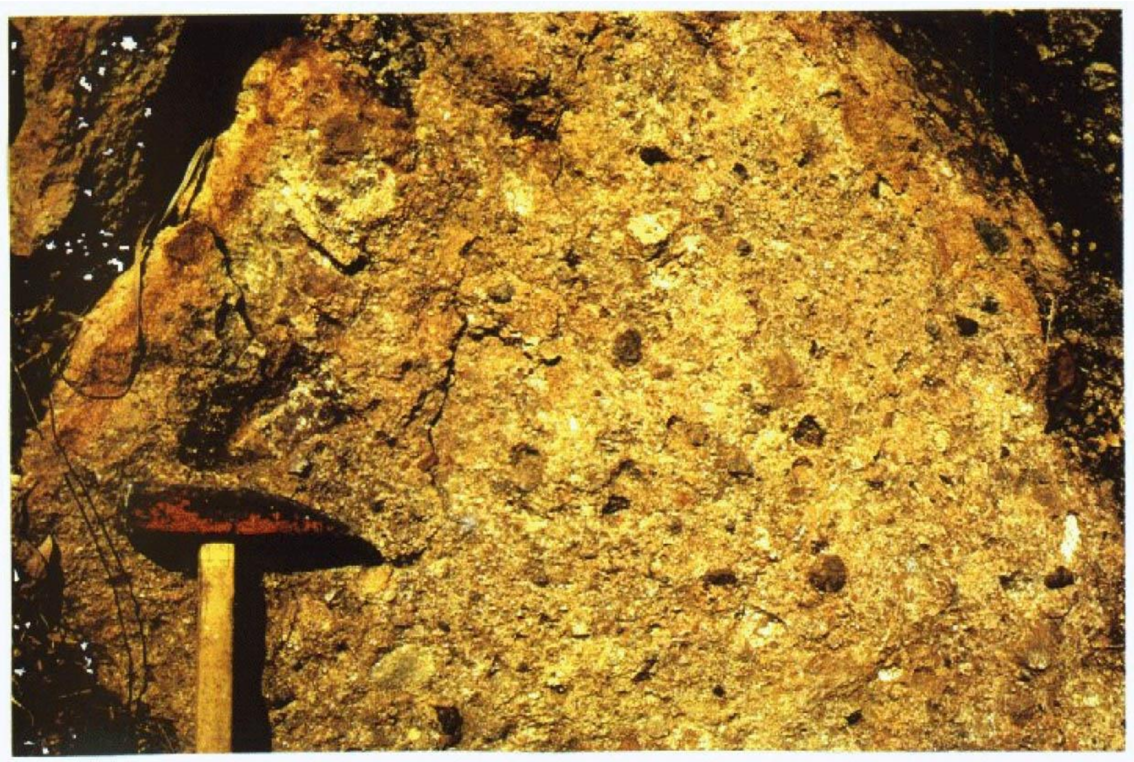

Plate 3b. Poorly consolidated crystal tuff with scattered well-rounded pebbles of volcanic rock and fine intrusive. Crystals are mainly plagioclase and quartz. Saraguro Group. Tres Chorreras [6635-96498]

3.8.1 Las Trancas Formation (new)

It comprises andesitic to dacitic, lithic lapilli-tuffs, tuff-breccias, dacitic to rhyolitic tuffs, conglomerates and sandstones. It contains much metamorphic rock detritus. The outcrop runs from the coastal plain, through La Rica, to its thickest development at the Las Trancas type area (Table 2). Farther northeast, the quantity of interbedded sedimentary rock is very variable and on the map the formation is depicted interdigitating with the undivided Saraguro Group. On the watershed to the northeast [6643-96571], only 4 km from Las Trancas, there is virtually no sedimentary material. The formation appears to be constrained to the west of the Chaucha-Río Jérez Lineament (Section 5).

The base is marked at Las Trancas [6582-96525] by conglomerates rich in metamorphic debris. The remainder of the formation is not well-exposed at Las Trancas, but the surface is littered with large boulders which are approximately in situ. It is dominated by green tuff-breccias and very poorly sorted conglomerate/boulder beds. Tuff-breccias at [6588-96514] are typical, comprising well-rounded to angular cobbles of variolitic basalt and microgabbro identical to lithologies of the Bella Rica Basalts. There are fewer clasts of micaceous psammite, abundant strained quartz and a few clasts of epidote/chlorite-altered intrusive rock (WP-252). Nearby [6586-96517], there are exposures of a few metres of massively bedded, poorly sorted conglomerate and coarse sandstone, rich in cobbles of coarse muscovite schist, weakly foliated muscovite gneiss and volcanic rock.

In the Ríos Margarita and Pagua, upstream of San Miguel de Brasil, the formation is mainly sedimentary. Exposure is poor, but there is much sandstone float. About 2 m of coarse massive sandstone, rich in quartz, muscovite, feldspar and acid volcanic fragments, are exposed at [6441-96551]. The assemblage of boulders here includes tuffaceous conglomerates rich in metamorphic clasts and vein quartz, coarse to fine green tuffaceous sandstones with sparse plant fragments, purple/red micaceous silty mudstones with carbonaceous seams and plant fragments. Samples (WP-451) submitted for micropaleontology were barren. The Río Margarita [6440-96572] shows a similar boulder assemblage.

South of San Miguel de Brasil, low cliffs [6418-96552] beside the coastal plain alluvium display about 15 m of massively bedded conglomerates which comprise well-sorted, well-rounded chert and vein quartz clasts mainly less than 30 mm in diameter. Good imbrication implies palaeocurrent towards 258°.

3.8.2 Portovelo Unit (new)

The main outcrop occupies the area from the Cordillera de Chilla [6550-96140] south to Zaruma and Portovelo. The unit is faulted against metamorphic rocks to the south, along the Piñas-Portovelo Fault System, and overlies the El Oro metamorphic complex unconformably in the Río San Luis [6721-95931] and at Salvias [6620-95964]. There is no age control on the unit. Previous workers have included this sequence within the "Celica Formation" (DGGM, 1982), the Piñón Formation (DGGM, 1973b; DGGM, 1975a) and "Saraguro Volcanics" (BGS and CODIGEM, 1993a).

The estimated minimum thickness is at least 5 km. This is based on the section between the Río San Luis and Zaruma [6547-95925], where the regional dip, defined by minor sedimentary intercalations and welding in ash-flow tuffs, is constantly gentle, or moderate, to the west. Rocks are very poorly exposed and typically spheroidally weathered, but where fresh, they are exceptionally tough. Massive, porphyritic blue-green andesitic lavas and crystal tuffs dominate. They have common plagioclase, amphibole and augite phenocrysts. Chlorite-filled vesicles, with irregular forms, give some of the lavas a jigsaw appearance. The crystal tuffs have small andesite fragments and sparse large quartz crystals. Andesitic lapilli-tuffs are rare (Plate 2a).

The unit shows limited hydrothermal alteration to epidote, chlorite and calcite. Epidote replaces the plagioclase phenocrysts. Augites and amphiboles are replaced by chlorite and epidote (e.g. WP-1548). Disseminated pyrite is common, especially concentrated in the mafic minerals. Pumpellyite and prehnite are also reported (Aguirre, 1992). Clay-altered andesites, in haloes around the rhyolite intrusions and epithermal veins of Zaruma-Portovelo, are extremely difficult to distinguish from the rhyolites (Section 4.2; Plate 1b). Zeolite spots have been noted in some thin sections (WP-1548).

Pillow lavas crop out in the Río Salati [6587-95869] east of Zaruma, comprising porphyritic basaltic andesites, with pillows about 2 m in diameter. In thin section, the rock displays a chilled, quenched texture and a flow foliation (WP-1539). The mafic phenocrysts are completely chloritised and zeolite amygdales are widespread.

This dominantly andesitic unit also includes dacitic and rhyolitic tuffs. Excellent exposures on Cerro Nudillo [6691-95885] comprise a pumice-rich, welded ash-flow tuff about 100 m thick, with scattered large quartz crystals. A vitroclastic texture is preserved. The same packet of dacitic to rhyolitic tuffs is exposed in a road [6633-95935] northeast of Guizhaguiña. It comprises at least two ash-flow tuffs, totaling 100m. The lower is rich in large bipyramidal quartz crystals and sparse biotites, the upper is rich in amphiboles, feldspars and fewer quartzes. A 0.6 m thick purple mudstone separates the two units. A second major packet of dacitic to rhyolitic tuffs occurs northeast of Salvias [6643-95993]. About 300 m thick, it comprises welded ash-flow tuffs with common pumice fragments, amphibole, quartz and plagioclase crystals.

The unit is hornfelsed by granodiorites in the Río San Luis [6721-95931] and carries abundant epidote and muscovite (WP-1545). Other hornfelsed flinty andesites occur north of the Río San Luis [6693-95948]. Disseminated pyrite is abundant and a granoblastic texture is visible in the matrix (WP-1525). Amphibole phenocrysts are altered to act + chl + sphene + pyr. The two geochemical analyses from the unit, plotted on a $SiO_2/Na_2O + K_2O$ diagram (Le Bas et al., 1986), confirm an andesitic composition, verging on basaltic andesite (Appendix 2).

3.8.2.1 Interpretation: The unit is interpreted as part of a calc-alkaline volcanic arc developed on metamorphic basement. The extensive propylitic-type alteration taken with the scarce pillow lavas, suggests the sequence is at least in part marine.

3.8.3 Plancharumi Formation (Dunkley and Gaibor, 1997)

It comprises a sequence of rhyolitic volcanoclastic deposits, fluvio-lacustrine sediments and rhyolitic lavas and breccias. It is overlain unconformably by the Jubones Formation. The best exposures are to the north of the mapped area from where a fission track zircon age of 25 ± 1.1 Ma has been reported (Dunkley and Gaibor, 1997).

3.8.4 La Fortuna Formation (new)

This is a welded rhyolitic ash-flow tuff with common quartz crystals. The formation replaces the “La Fortuna Volcanics” (DGGM, 1980c) which were similarly defined. The main outcrop is an outlier which caps the crests of the west flank of the Western Cordillera. It occurs only north of the Río Jubones, lying with strong angular unconformity on older Saraguro strata and dipping constantly, and gently, towards the coast, “islands” also occur within the coastal plain alluvium, for example south of El Guabo [6330-96400 and 6320-96357]. The outcrop can be traced inland as far as Loma de Bunques [6563-96500], at over 3000 m altitude.

The tuff is generally strongly weathered, forming decomposed rock and white soil. Where fresh, for example near Pasaje [6324-96354], it is pale grey and siliceous with scattered plagioclase, embayed quartz and sparse biotites. Columnar joints and moderate welding are well-developed near La Tigrera [6492-96449]. In thin section, there is a clear eutaxitic welding foliation and scattered embayed quartz crystals and sparse small biotites (WP-176). Close to Loma de Bunques, over 20 km east of the Río Jubones locality, the textures are identical (WP-1222).

The thickness is estimated at up to 600 m, for example south of La Tigrera [6510-96432].

The formation is dated by fission track at 23.2 ± 0.8 Ma (Early Miocene) (Appendix 1). Unfortunately, it wedges out before the most westerly exposures of the Jubones Formation. Therefore, the age relations are nowhere seen. The respective age dates for the formations have overlapping error bars, implying that they are broadly contemporaneous. Geochemically, they are also very similar, despite the much lower content of quartz crystals in tuffs of the La Fortuna Formation, plotting almost together on the $SiO_2/Na_2O + K_2O$ diagram, well into the rhyolite field (Le Bas et al., 1986; Appendix 2).

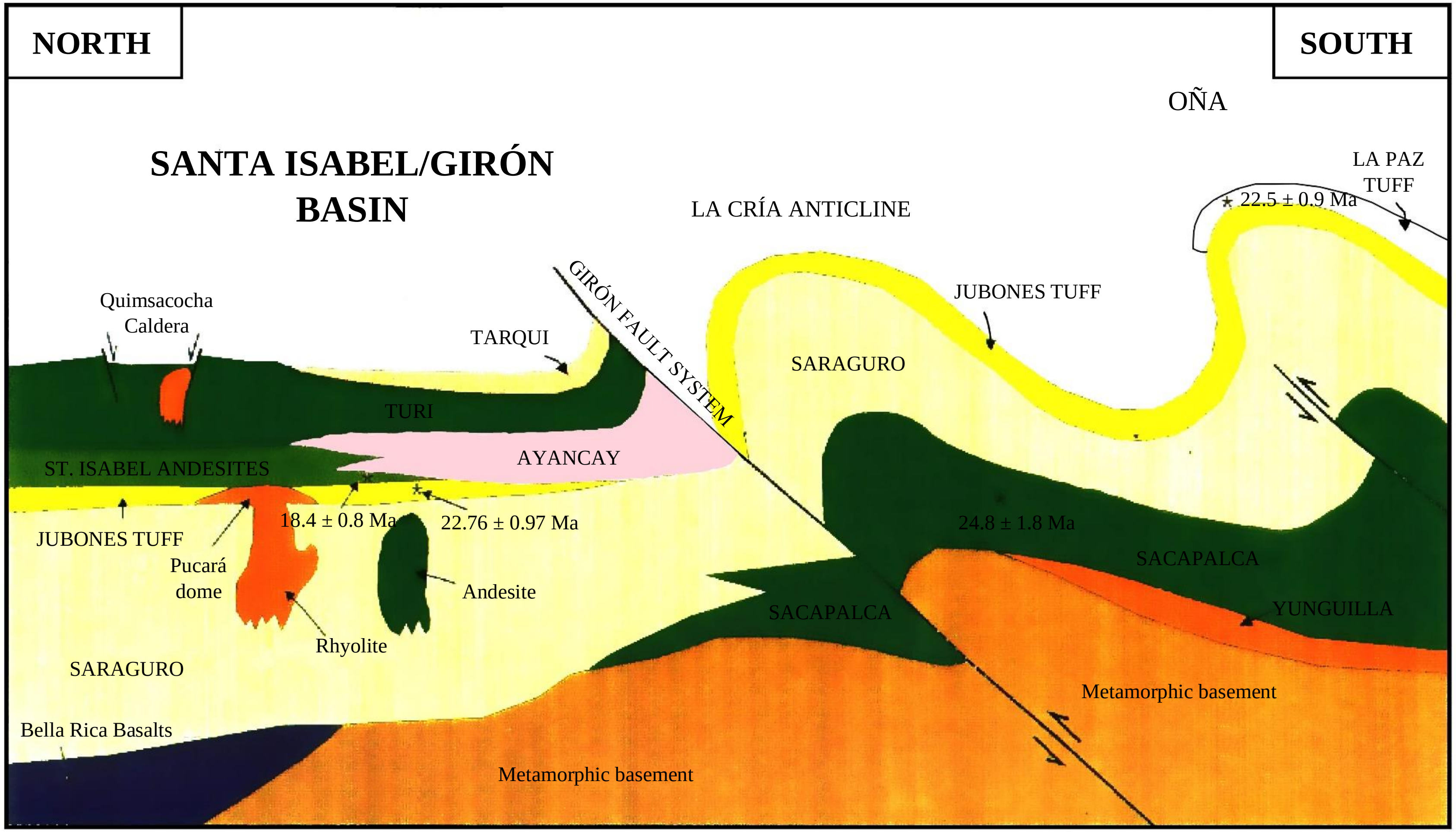

Figure 4. Cartoon of the stratigraphy and structure of the Santa Isabel basin

3.8.5 Jubones Formation (new)

This is a rhyolitic crystal tuff, rich in plagioclase, quartz and biotite crystals. It is an important marker and has a large outcrop. The mapped surface area is at least 2700 km^2 (Figure 5). This includes an extension north of 3°S, around Pimo (Dunkley and Gaibor, 1997; BGS and CODIGEM, in press b). The tuff is thickest east of Pucará where it attains at least 500 m (Figure 5). It thins towards the north and is generally cut out beneath unconformities. It wedges out beneath massive andesitic breccias of the Santa Isabel Formation at Quinuas [6663-96508], beneath the Turupamba and Quimsacocha Formations west of the Quimsacocha Caldera, and beneath the Turi and Turupamba Formations at Pimo (Dunkley and Gaibor, 1997). Towards the axis of the Ayancay Group basin the tuff was cut out by erosion prior to deposition of the andesites of the Santa Isabel Formation.

North of the Río Jubones, the tuff does not occur immediately east of a line between Gañarín [6800-96353]. Cañaribamba [6850-96427], Huasipamba [6863-96483] and Tres Lagunas [6853-96554]. This is despite the fact that it is generally thickly developed to the west. This reflects uplift and erosion along the Gañarín Belt (Sections 4.2, 6.2) prior to the deposition of the Santa Isabel Formation (Plate 5a, Figure 5).

South of the Girón Faulty System, the formation re-emerges and maintains a thickness of about 160 m. Above the Río León, it was previously mapped as the Tarqui Formation (Kennerley et al., 1973). The most southwesterly outcrop, an unusual wedge about 1 km wide, occurs at Guanazán [6678-96176] (Figure 5). The geometry has not been studied in detail, but it seems to be an erosional remnant preserved between two fault strands of the Gañarín Belt. The exposures are distinctly banded tuffs. The welding foliation has been distorted by flow (rheomorphism) and is locally strongly folded, for example [6684-96163].

The type section, described in Section 3.8.6, is a roadcut east of Río Minas [6805-96320]. An almost complete sequence, with base surge, lag breccia and crystal tuff, is exposed. However, this three-part zonation occurs only here. Everywhere else, only the crystal tuff is present. The exposures on the Panamerican highway [7033-96250] north of the Río León, for example, comprise pink and cream, moderately foliated, plagioclase, quartz and biotite crystal-rich tuff with common elongated pseudoclasts and scattered angular andesite fragments.

The tuff is not generally affected by silicification, but northwest [6798-96593] of Pedernales there is an unusual zone of silicified joints. A well-exposed example [6798-96586] is vertical, 3 m wide and strikes 076°. It is part of a swarm of silicified joints or minor faults with similar orientation.

West of Santa Isabel, the Jubones Formation has been dated by K/Ar on biotite at 22.76 ± 0.97 Ma, earliest Miocene. Near Oña, it has been dated at about 23.0 ± 2.2 Ma (DH-486) (Hungerbühler, in prep; Appendix 1). A fission track date from immediately beneath gives 25.0 ± 0.9 Ma (Appendix 1).

Figure 5. Isopach map of the Jubones Tuff with the proposed site of the Jubones Caldera. Areas where the Tuff is absent mostly reflect post-depositional erosion. Gold prospects and alteration zones of the Gañarín Belt are shown. All thickness in metres.

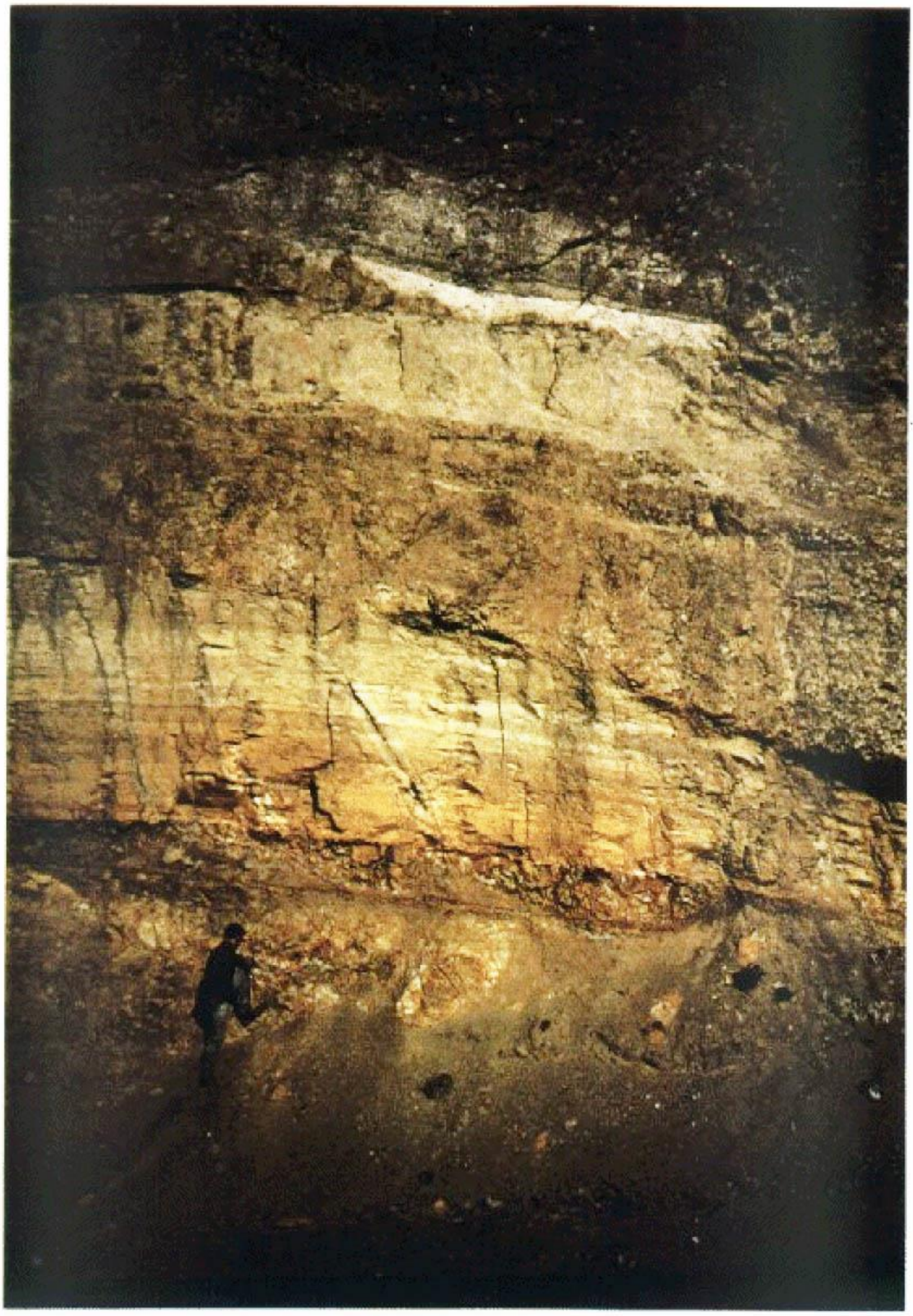

Plate 4. Basal surge, up to 2.5 m thick, of the Jubones Tuff Formation. It begins about 1.5 m above the head of the geologist and is strongly scoured by the cobble-rich portion. It displays large-scale, low angle cross-stratification and contains silicified trees in the lower 0.3 m. Río Minas [6808-96323]

Plate 5a. View of the Jubones Tuff [6806-96318] at the Río Minas. The Tuff wedges out to the left (north), cut out by an angular unconformity beneath the Santa Isabel Andesites. The yellow basal surge is visible in the road (Plate 4)

Plate 5b. Typical Saraguro Group strata in the Río Tenta [6884-96048], northwest of Saraguro. Cliff is ca. 500 m high. A thick welded ash-flow tuff, with columnar joints, is overlain by four thin flow units. They are interpreted as products of the same eruption phase. Above, a prominent bench marks sedimentary deposits. A further three ash-flow tuffs complete the sequence

3.8.6 La Paz Formation (new)

This is a rhyolitic ash-flow tuff, rich in plagioclase and quartz crystals. It was previously included the Pliocene-Pleistocene Tarqui Formation (DGGM, 1974). The tuff is largely flat-lying and crops out only south of the Girón Fault System (Figure 4). It occupies the high páramo between Loma Tiopamba [7200-96477], south of Cumbe, and Filo de Huaca [7032-96020] near Saraguro. Small outliers, overlying andesitic tuffs of the Sacapalca Unit, occur near Girón [7075-96506 and 7096-96534]. The dip increases towards the Girón Fault. Exposures with 45° dip occur below Chachi [7027-96448].

The tuff weathers to a cream- or buff-coloured decomposed rock. The outcrop is characterized by the abundance of coarse (quartz) sandy soils. Where fresh, for example north of La Paz de la Independencia [7075-96345 and 7058-96351], the rock is commonly columnar jointed and displays a weak welding foliation. It is rich in large plagioclase and bipyramidal quartz crystals. Lithic lapilli are uncommon. The magnetite content is high and magnetite is common in the soils.

The slightly discordant base is well exposed northeast of La Paz [7128-96387]. The basal metre contains coal fragments, carbonized trees, and many small lithic lapilli. It overlies tuffs with thin coals (Section 3.8.6). On the north side of the Río León [7020-96250], the La Paz Formation overlies the Jubones Formation, but farther north it steps down onto older rocks and the Jubones Formation is cut out.

The maximum thickness, about 400m, occurs southwest [7030-96140] of Oña. Southwards, towards Saraguro, it declines to less than 200 m. The original extent, based on the outcrop, was at least 800 km^2.

Correlation problems occur between La Paz and Cumbe because of the difficulty in distinguishing the tuff from sub-volcanic intrusions. Hence, the formation is not carried this far north on the geological map, wedging out in the undivided Saraguro Group.

A fission track date of 22.5 ± 0.9 Ma, from west of Oña, indicates an earliest Miocene age for the La Paz Formation (Appendix 1).

3.8.6.1 Interpretation: Ash-flow tuffs, probably caldera outflow facies, dominated deposition of the Saraguro Group. Unfortunately, in only one case, the Jubones Formation, it is possible to relate an individual ash-flow tuff to a volcanic centre/caldera. The clusters of age dates indicate that huge thicknesses were deposited in short periods. Large periods of time are therefore represented by major disconformities. The angular unconformity beneath the Jubones Formation alone probably represents a gap of about 4-5 Ma. The andesitic-dominated sedimentary sequences, such as the Santa Isabel “proto-basin”, are interpreted as the outwash of andesitic fissure eruptions or stratovolcanoes.

The bulk of the group was deposited in a terrestrial setting. However, sparse grey turbidite interbeds in the lower part (Table 1) suggest initiation of volcanism in a mixed terrestrial and marine setting. The Las Trancas Formation is probably an alluvial fan and fluvial sequence.

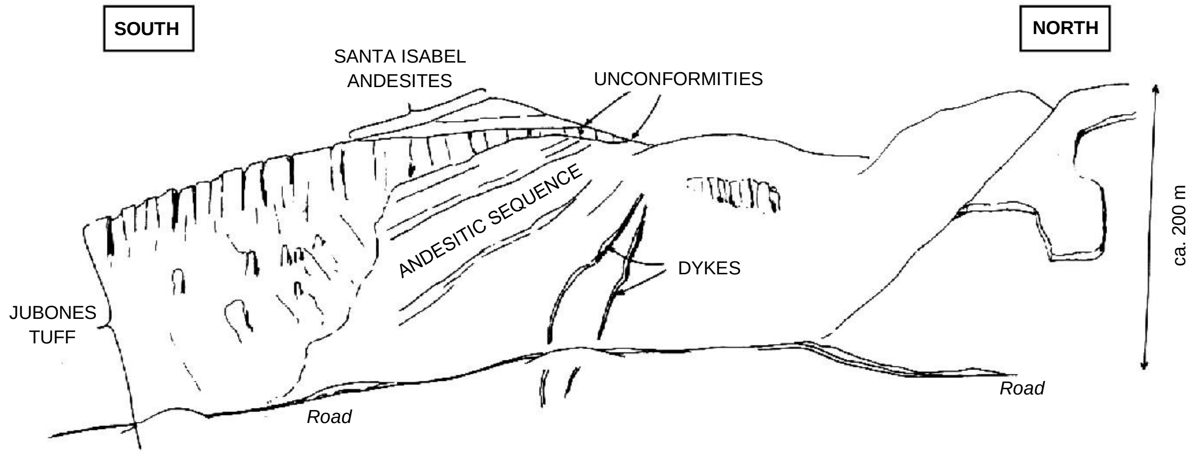

Figure 6. West wall of the Río Minas, southwest of Santa Isabel.
Looking west from [6806-96320]. It shows the tilted fault blocks, related to caldera formation, which existed immediately before deposition of the Jubones Tuff.
The almost vertical lines within the tuff are columnar joints

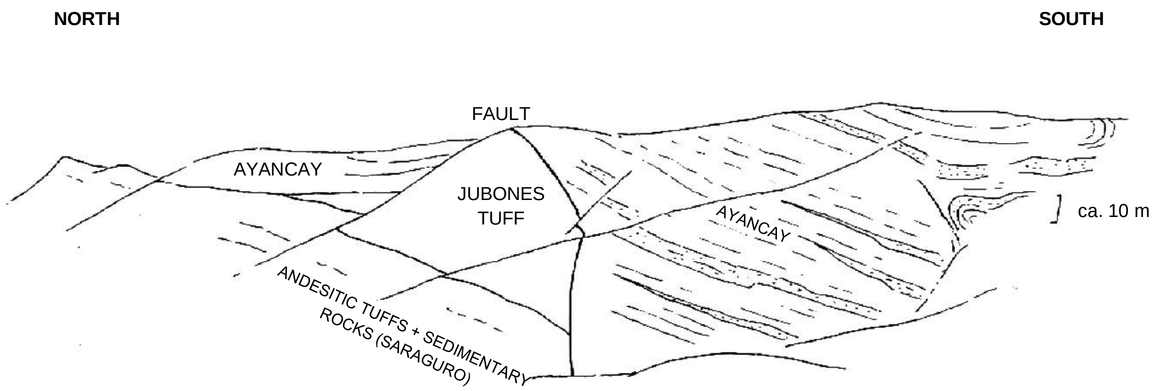

Figure 7. Sketch of the area east of San Sebastián de Yuluc, from a viewpoint [6763-96285].
Note how the Jubones Tuff wedges out completely towards the left (north), beneath the angular unconformity at the base of the Ayancay Group

Syn-depositional tectonism was strong, switching from extensional to compressional. Vertical and folded strata underlying the horizontal Jubones Formation at Pedernales indicate how strong some of the compressive episodes were. The Girón Fault System played an important role, with probable pre-Jubones Formation compression at La Cría (Figure 8). To the north, the highest preserved Saraguro Group is the Jubones Formation whereas, southwards and eastwards, acid tuffs (La Paz Tuff) are preserved above the Jubones Formation. It seems that the north side suffered uplift and erosion that preceded deposition of the Santa Isabel Formation.

There is evidence that the Saraguro Group was constrained in a basin between the Cordillera Real and the uplifted western part of the Western Cordillera. The removal of large thicknesses of strata from the west side of the Western Cordillera prior to the start of deposition is implied by the absence of Cretaceous turbidites, Celica, Quingeo and Sacapalca. The preservation of these formations, albeit in remnants, towards the Cordillera Real, implies greater uplift in the west, perhaps along a major reverse fault at the foot of the Cordillera. This is strongly supported by the westward overstep of the Las Trancas Formation onto progressively older Saraguro Group rocks and, finally, onto metamorphic basement near Ponce Enríquez.

The Saraguro Group thins and contains a greater proportion of sedimentary interbeds, towards the east. It is estimated to be very thin, less than 500 m, beneath the Cuenca basin (Hungerbühler and Steinmann, 1996). Maps of the Cuenca Basin (DGGM, 1980b; DGGM 1980c) also depict a thickness of up to only 1 km, declining to the east. This implies that the Saraguro onlaps onto the Cordillera Real metamorphic rocks.

The minimum eruptive volume of the Jubones Formation is estimated at 350 km^3. An equal or greater volume may have been lost through erosion. Such an eruption was probably a caldera-forming event. Relationships between eruptive volume of ash-flow tuffs (“ignimbrites”) against caldera diameter (Cas and Wright, 1987), imply a likely source caldera (ring fissure type) of 15 to 20 km in diameter. The trees at the base of the base surge give an indication of the direction of the initial blast. They are aligned 300° to 042°, with an average of about north-northwest. This spread may reflect variation, or perhaps they are forked trees. Since they were probably knocked flat by the original low-density blast of the surge, without being involved in transport, the flow direction was either towards the north-northwest or south-southeast.

The best indication of the whereabouts of the caldera is given by the isopach map, which shows greatest thicknesses around Pachagmama, Río San Francisco and Río Minas, on the Gañarín Belt (Figure 5; Section 6.2). In the same area there is evidence of listric-style extensional faulting (see details section). This caused the rotation of large fault blocks and the Jubones Formation accumulated in the resultant topography (Figure 6). The absence of major erosion in this time interval indicates that extensional faulting and eruption were almost instantaneous. Mapped listric faults dip towards the centre of the proposed caldera and backtilted strata dip away from it.

The proposed caldera includes the only area where a base surge and lag are recorded, as well as a concentration of sub-volcanic rhyolite intrusions.

The similarity in age and chemistry between the tuffs of the La Fortuna and Jubones Formations suggests that the former may also have emanated from the Jubones Caldera, though it is not clear whether it preceded, or followed, eruption of the Jubones Formation.

3.8.6.2 The Santa Isabel proto-basin: The best exposures occur in the precipitous cliffs of the Río Jubones below Abañín [6680-96334 to 6735-96326] and around the site of the Jubones Caldera. At Pachagmama, growth faults, striking broadly east-west and dipping moderately southwards, have thicker accumulations of tuffaceous sandstones in their hanging-walls. Syn-sedimentary wedges of sandstones and debrites are also developed. Some hanging-walls are backtilted by some 20°, so that they dip towards the growth faults. A large rock face of debrites at [6742-96320], about 200 m high, displays an angular unconformity which truncates a gentle syncline, testifying to strong syn-depositional faulting. Intrusion of the Pachagmama rhyolite upturned some strata in a zone a few hundred metres in width, but had little effect on the overall structural geometry.

Close to the union [6701-96343] of the Río San Francisco and Río Jubones there are exposures of a debrite, possibly a lahar. It comprises a muddy tuff, rich in feldspar and amphibole, with abundant yellowish tuff clasts up to 0.2 m in size. Clast margins are irregular, implying incorporation in a soft state. Andesitic lava clasts, with red oxidised rims, are also common. Between the river and [6706-96327], road exposures display sandstones, conglomerates and muddy crystal tuffites. There are numerous examples of channelling and syn-depositional faulting. Some well-bedded strata pass laterally into debrites by slumping.

Exposures in the Río San Francisco, east of Pucará, show the 250 m of strata beneath the Jubones Formation. Sedimentary rocks are less well-developed and are mainly pale green tuffaceous mudstones with abundant accretionary lapilli, some broken, up to 15 mm in diameter, for example [6748-96420]. The lowest strata comprise a massive dacitic tuff with abundant green and red lithic fragments. This is overlain by flow-banded purple andesite which closely resembles bedded tuff because of crystal segregation into bands. The flow banding is broadly horizontal, but locally [6746-96426] turns vertical. The axial planes of these flow folds strike roughly east-west. Fold vergence shows flow towards the south. In thin section, the lavas comprise a flow-banded felt of feldspar microlites with strongly zoned feldspar phenocrysts (largely altered to calcite) and amphibole phenocrysts (altered to chlorite and opaque ore) (WP-169, 209).

In the Río Jubones northeast of San Sebastián de Yuluc, the same elements exist; volcanoclastic sedimentary rocks and andesites. There are some problems distinguishing intrusive from extrusive andesite, but there are undoubted feldsparphyric lava flows. In the Cuenca-Machala road [6778-96307], the sequence begins east of a northeast-striking fault, part of the Gañarín Belt, with more than 50 m of pale green debrites with abundant rounded cobbles of andesite. The matrix is rich in feldspar crystals and tuffaceous material. The debrites are overlain by 15 m of well bedded, bright green, copper-enriched coarse sandstones and debrites. A further 200 m of debrites follow, with two or three purple weathered andesite lavas, 3 to 30 m thick. In the hillside opposite, south of the Río Jubones, the lava flows, locally columnar jointed, pinch and swell, some wedging out entirely. The sequence is capped by the Jubones Formation.

3.8.6.3 Type section of the Jubones Formation: The type section begins with a classic basal surge deposit of poorly cemented coarse crystal tuff, 1-3 m thick, with wavy, large-scale, long wavelength cross-stratification, interpreted as antidunes (Plate 4). Comprising grains of feldspar, biotite, quartz and rock fragments, it overlies 0.2 m of mudstone of possibly lacustrine origin. Silicified tree trunks are common in the lower 0.2 m. Each tree is strongly flattened, with a depth/length ratio of about 1:2.5 or 3. The alignment of 7 trees was measured: 004°, 160°, 120°, 121°, 042°, 145° and 031°. The crystal tuff is overlain, with erosional contact, by a reddish zone of crystal-rich (quartz, feldspar and biotite) agglomeratic tuff with abundant well-rounded blocks up to 0.7 m in size. The zone, interpreted as a co-ignimbrite lag deposit, is 11 m thick in the road, but thicker only a few hundred metres to the north and south (Plate 5a). The clasts include andesite lava, rhyolitic tuff/lava and a few of red mudstone. There are distinct cobble-rich and cobble-poor bands, implying fluctuation in the pyroclastic flow.

Above the agglomerate, the main body of the tuff comprises cream crystal-rich tuff with sparse paler clasts of the same composition. Many may be pseudo-clasts, the product of recrystallization. No degassing pipes are seen. A planar foliation, largely defined by the aligned ‘clasts’, is apparent. Large scale columnar jointing, with columns more than 1 m in diameter, is present throughout, but becomes better defined upwards in the body and is present right up to the eroded top. A thin section (WP-113) shows large crystals of broken plagioclase, embayed quartz and biotite. The biotite is commonly bent by compaction. The matrix comprises chlorite rosettes, the result of devitrification. The recrystallization, a regional feature in many rhyolitic tuffs and rhyolites of the Saraguro Group, means that few shards can be distinguished. About 100 m of the main body of the tuff is preserved at this locality; only a few hundred metres north, the entire tuff has been eroded beneath the profound angular unconformity at the base of the Santa Isabel Formation. In the west wall of the Río Minas, about [6800-96320], the tuff appears to infill a pronounced topography (Figure 6).

3.8.6.4 La Paz, Cumbe and Tarqui: There is a distinct change in the Saraguro Group from La Paz towards Cumbe, with incoming of beds of coal and tuffaceous sedimentary rock. Beneath the La Paz Formation, north of La Paz [7128-96387], there is a coal, 0.4 m thick, underlain by a further 20 m of bedded and welded acid tuffs, both types lithic-rich, and beds of pink mudstone. A lithic tuff, about 80 m thick, lies beneath. This moderately welded rock, possibly the Jubones Formation, is rich in flattened and aligned lithic fragments, up to 0.5 m in length, including quartz/biotite tuff, pumice, mudstone and pale brown, strongly welded tuff. The matrix, which is pink, fine-grained and probably vitroclastic, is rich in quartz and biotite crystals. The lowest part of the sequence, at [7138-96386], is a rotten-weathered basalt with abundant vuggy agates and agate veins. It may be an intrusion, because of faintly flow-banded, intrusion of similar composition occurs nearby on the Nabón road [7147-96387]. In thin section (WP-322), the latter comprises a groundmass of feathery plagioclases and interstitial augite with scattered altered olivines.

Northeastwards, the La Paz Formation overlies a different sequence, more sedimentary in character. Good exposures occur between the high point of the Panamerican highway [7196-96481] and Cumbe. The rocks are breccio-conglomerates, dominated by acid tuffaceous material, pebbly acid tuffs, tuffaceous sandstones, cream mudstones and thin coals [7190-96500]. Unidentified plant fragments are common in some places, for example [7203-96514].

On the northwest side of the Yunguilla/Quingeo Cumbe Inlier, there is a strip of deeply weathered acid tuff and conglomerate. About 3 km wide, it was previously assigned to the Tarqui Formation (DGGM, 1974). It is thrown against the Ayancay Group by the Girón Fault. The sequence, about 1.25 km thick, dips gently (10-30°) to the northwest. The conglomerates are well-exposed on the Cuenca-Machala road, for example at [7171-96626]. At [7142-96593] tabular cross-stratification in sandstones indicates flow towards 160°. Structural considerations imply that the entire sequence is beneath the La Paz Formation and hence entirely Saraguro.

The type section of the Tarqui Formation [7198-9667], a few kilometres to the northeast of Cumbe, comprises similar rocks, also overlain by the Ayancay Group. We interpret the strata as Saraguro Group. This is supported by the observations in the Cuenca Basin that the Tarqui is Late Miocene or younger (<10 Ma) and clearly overlies the Ayancay Group.

3.8.6.5 The páramo of Chilla, Manú and Selva Alegre: The acid tuffs of the páramo south of Chilla, Guanazán and Manú and west of Selva Alegre were included by Kennerley et al. (1973) in the Chinchillo Formation. We abandon this term because the tuffs are indistinguishable from Saraguro Group strata. Furthermore, the inlier of the Jubones Formation at Guanazán [6680-96165], occurs within the "Chinchillo Formation". A fission track date of 20.7 ± 2.4 Ma (Appendix 1) from an andesite/dacite lava at a similar level to the Jubones Formation at Guanazán, but 4 km east, on the Manú side of a major watershed [6727-96144], strengthens the case.

The most spectacular sections occur between Tauracocha [6703-96036], Sabadel [6718-96057] and the Rio Pilincay [6660-96110]. The flat-lying sequence begins at Tauracocha with about 200 m of porphyritic dacitic/andesitic lavas. They show amphibole, partly altered to chlorite, plagioclase and sparse quartz phenocrysts in a very fine holocrystalline matrix (WP-689). The sequence continues at Sabadel with about 500 m of dacitic crystal tuffs, rich in plagioclase and amphibole crystals. Three or four ash-flow units are visible in the cliff. These are overlain by about 140 m of well-featured, thinner units of variably welded, pumice-rich ash-flow dacitic tuffs [6730-96085].

North of Gualel a fluvial sedimentary sequence occurs within the Saraguro Group. Like the Las Trancas Formation, it is rich in metamorphic debris. At Cordillera Payana [6737-95884] it attains about 160 m and comprises pebbly sandstones and coarse conglomerates rich in vein quartz, gneiss, psammite, schist, feldspar and muscovite. Interbeds of black and dark grey mudstone and purple muddy andesitic debrites are common. In thin section, a sandstone from [6744-95886] shows abundant muscovite, sparse biotite and sparse zircon (WP-1513). The sequence is overlain by flat-lying dacitic tuffs. The base of the fluvial sequence was not seen at Payana, but samples collected by stream sediment samplers from the Río San Luis basin imply that it is underlain by more acid tuff. For this reason, the sequence is included within the Saraguro Group. However, it is possible that it is a Cretaceous unit.

3.8.6.6 Zaruma-Piñas: West of Zaruma, crystal tuffs that were previously included within the Celica are now considered as Saraguro. The outcrop is well-featured, with units dipping west at gentle to moderate angles. The olive-green tuffs have a spheroidal weathering aspect and are not as tough as the Celica rocks. On the main Piñas-Zaruma road [6505-95912], massively bedded andesitic crystal tuffs contain graphitic phyllite lapilli, perhaps ripped from the sides of the source vent. They overlie a debrite comprising large boulders of pale (dacitic?) lava, andesite and cherts within a red mudstone matrix. A few hundred metres west, at El Portete [6502-95916], a ca. 50 m thick, columnar jointed dacitic ash-flow tuff yielded a fission track date of 21.5 ± 0.8 Ma (Appendix 1).

A rhyolitic ash-flow tuff, at least 200 m thick, crops out in outliers along the Piñas-Portovelo Fault System and is locally, for example [6478-95916], caught up as wedges within fault strands. It has a coarse, non-welded vitroclastic texture, with sparse pumices (WP-1641). It is flat-lying and seems to overlie the Saraguro tuffs unconformably, cutting across the strike of the former at El Portete [6495-95905], for example. West of Salati [6595-95863] it forms a gentle footwall syncline to the Piñas-Portovelo Fault System. It was included previously in the Tarqui Formation (DGGM, 1980a). Although no age date is available, we include it within the Saraguro Group because of the lack of Tarqui activity this far south.

3.8.6.7 San Gerardo: This [6519-96631] area of deeply weathered andesitic tuffs and dacitic (quartz crystal) tuffs separates the outcrops of the Bella Rica Basalts. The tuffs crop out only in the highest parts, suggesting that they are an outlier of the Saraguro Group, lying with angular unconformity on the Bella Rica Basalts.

3.9 Santa Isabel Formation (new)

This formation comprises massive, deeply weathered, olive-green andesitic tuff-breccias with scarce andesite lavas and sedimentary rocks. It was previously included in the "Saraguro Formation" (Kennerley, 1973).

The outcrop can be traced from La Cria [6903-96268], in the southeast, to Zula [7042-96492], near Girón. Westwards, towards Uzhcurrumi [6583-96312], there is also an extensive outcrop (see details). Near Girón [7023-96512], there is a small inlier. There are no outcrops southeast of the Girón Fault System. The formation interfingers with the Ayancay Group in the Santa Isabel to Girón area so that there are upper and lower tongues (Figure 4). This leads to a complex situation: in the west, the andesitic rocks are overlain by the Ayancay Group. Between Santa Isabel and Girón, however, they overlie the Ayancay. The critical area is at Santa Isabel, where wedges of Ayancay red-beds can be mapped within the andesites [6867-96385 and 6872-96406]. All pinch out towards the north and west, the upper and lower tongues of the formation merging.

Typical lithologies, west of Santa Isabel [6860-96384], are soft, rubbly weathering andesitic tuff-breccias. Angular fragments of andesite can be distinguished, with difficulty, in a matrix packed with feldspars and amphiboles. The rocks are white-stained, calcite-veined and highly fractured.

The base of the formation is exposed in the Río Jubones [6803-96303], where, an impersistent basal conglomerate, up to 8 m thick, overlies the Jubones Formation with strong angular unconformity. It is very coarse, poorly sorted and polymict. Well rounded cobbles, up to 0.5 m, are mainly feldspar-phyric andesite, sandstone, mudstone and andesitic tuff-breccia. The matrix is tuffaceous, with abundant angular fragments and crystals of amphibole. There are no clasts of the Jubones Formation.

In much of the outcrop, the lowest strata are massive yellow tuffaceous mudstones, about 100 m thick. The sequence is well-exposed near Gañarín [6788-96337] and in the Río León [6881-96290]. It also occurs on both sides of the La Cria Anticline, for example La Cria [6902-96266], Loma de Lagunas [6883-96296] and Las Cochas [6833-96216]. Gastropods and fish teeth are reported (pers. comm. Hungerbühler, February, 1997). The yellow strata are capped by a remarkable sequence, 8 to 20 m thick, of purple/red, extremely tough, fine tuffs, tuffaceous conglomerates and sandstones (Plate 10). The clasts comprise fine acid tuff, rhyolitic tuff-breccia, quartz crystal tuff and feldspar-phyric andesite. There are subordinated beds of finely laminated acid tuff and red mudstone.

The formation is typified in the northwest, for example Pindochupa (see details), by large-scale disruption and a greater content of sedimentary rocks. A mélange of red mudstone, andesitic debrites and sandstone is common between the Río Minas and Shadan [6828-96327]. These directly overlie the Jubones Formation and large rafts of the tuff are incorporated locally. A few miniature syn-depositional graben occur in the Cuenca-Machala road. At [6835-96340], a wedge-shaped graben, 8 m wide, occurs within massively bedded andesitic debrites. The graben is draped by younger strata, showing that it was syn-depositional. The defining faults strike northwest and north.

The maximum thickness of the formation is about 400 m. In the northeast, where it is cut out by the Turi Formation, the thickness drops steadily from 400 m at the Río Rircay [6983-96430], to nothing near Santa Teresa [7044-96497], about 8 km away.

A fission track date of 18.4 ± 0.8 Ma (Hungerbühler, in prep.) is reported from near the base of the formation. At the Río Rircay roadbridge [6983-96430] the upper tongue was dated by K/Ar at 14.2 ± 0.5 Ma (Kennerley, 1980; Appendix 1). A fission track age of 18 Ma is also reported from the red tuffaceous sequence at the top of the yellow tuffaceous mudstones (Hungerbühler, in prep.) Kennerley (1980) recorded a K/Ar date of 19.5 ± 0.4 Ma from east-striking andesite dykes at Pachagmama [6733-96325]. These dykes intrude pre-Jubones Formation strata and they may represent feeders for the Santa Isabel Formation. The northern limit of the Pucará rhyolite dome (Section 4.3) is also cut by similar east-striking andesitic dykes [6733-96446].

Plate 6a. Angular unconformity between the Santa Isabel Andesite Formation, pale grey and rubbly, at right, and the Ayancay Group. Loma Peña Blanca.
Looking southwest from [6845-96344]

Plate 6b. Ayancay Group fluvial sequence above the Río Jubones. The road in foreground cuts the Jubones Tuff. Above the Ayancay Group, yellowish soils mark the unconformable Uchucay Formation, dipping towards the left. Looking southeast from about [6795-96318]

3.9.1 Interpretation

The formation represents a return to the conditions that prevailed immediately before eruption of the Jubones Formation. Andesites and andesitic tuffs were erupted from stratovolcanoes or fissures and large proximal fans of andesitic debris accumulated in an unstable environment. Most of the tuffs are interpreted as proximal pyroclastic flows. Some elements, such as sandstones, conglomerates and red mudstones, are typical of the overlying Ayancay Group, suggesting a transition into an intermontane basin. Slumping was widespread and rafts of the Jubones Formation were incorporated. The yellow tuffaceous, gastropod-bearing sequence probably represents lacustrine conditions. The occurrence of these beds, and the purple tuffaceous rocks, on either side of the La Cria Anticline is significant. It demonstrates that the anticline, or precursor structure, did not exist during sedimentation, an important point considering the complexity of local tectonics. There clearly existed a fairly low, flat plain between (at least) La Cria and Gañarín.

3.9.2 Details

3.9.2.1 East of Uzhcurrumi: In the road section which climbs from Algodonal [6582-96312] to Abañín [6668-96316] there are many exposures of massive andesitic tuffs and lavas. At Union de Tamacado there is an intercalation of sedimentary rocks. Exposures [6632-96311] comprise more than 10 m of massively bedded conglomerate, with carbonized trees, above 2.7 m of grey and white mudstones and siltstones with many plant and coal fragments. A sample for micropaleontology was barren. The mudstones are calcareous, with common concretions. The thin sequence is not included in the Ayancay Group because massive andesitic tuff breccias reappear immediately above.

3.9.2.2 Pindochupa: North of the Cuenca-Machala highway, around a steep-sided ridge at Pindochupa [6818-96336], there is a relatively coherent sequence of sedimentary rocks below the red basal conglomerates of the Ayancay Group. The sequence is preserved in a miniature graben, triangular in plan and up to 500 m wide, developed within andesitic tuff-breccia. The graben, aligned southeast, closes to the southeast. There are about 60 m of conglomerates, boulder beds, pale green debrites and thin rhyolitic tuffs, probably of air fall origin. Virtually all the debris is andesitic. The coarsest boulder beds have well-rounded andesite boulders to 2.5 m in diameter.

3.9.2.3 Asunción: A circular structure, 7 km wide, is visible in the aerial photographs and drainage around Asunción. However, on the ground it is difficult to see. Furthermore, the area inside and outside of the structure comprises the same massive andesitic tuff-breccias. Locally, as at Arushumi [6931-96435], the breccia contains blocks of andesite up to 2 m in diameter. It may reflect a caldera, but there are no indications of the acid rocks normally associated with caldera formation.

3.10 Ayancay Group (UNDP, 1969c)

This comprises massively- to thickly bedded reddish conglomerates and buff sandstones intercalated with red, purple, cream and pale green mudstones and siltstones (Plates 6a, b and 7). There are also rare air-fall tuffs, gypsum beds and thin coals. The group is equivalent to the Santa Rosa and Mangán formations of the Cuenca Basin (Bristow and Hoffstetter, 1977; Bristow and Parodiz, 1982). It interdigitates with the Santa Isabel Formation.

The linear outcrop follows the north side of the Girón Fault System between Cuenca and Girón, broadening southwest into the Santa Isabel Basin. The axis of the basin is marked now by a major fold, the Girón Syncline.

The Ayancay Group shows distinct lateral variation. It is thickest and coarsest near the syncline axis, at the southern margin of the outcrop. More than 600 m of conglomerate-dominated beds occur around the Mina de Mármol [6825-96247] and the total thickness is estimated at about 1.5 km. The grain size and thickness decline northwards from the syncline. At the northern edge of the basin there is a gentler undulating angular unconformity, draping a distinct paleotopography (Plate 6a). There are fewer conglomerates and the sequence is coherent and continuous. For example, a single green feldspathic sandstone, 0.5 m thick, can be traced from the Río Jubones [6844-96313] at least 5 km to the north, in the Cuenca-Machala road [6832-96328]. The base is strongly unconformable, sedimentation initiating on the tilted, faulted and eroded Saraguro Group and Santa Isabel Formation (Figure 4; Plate 6a). An example of irregular paleotopography occurs at Loma Peña Blanca [6845-96337], where a paleoslope in the Santa Isabel Formation is exhumed. Almost horizontal sandstones, conglomerates and mudstones onlap onto a 30° paleoslope. Pockets of pebbly sandstone, comprising rock fragments, feldspar and quartz, cling to the slope.

Spectacular exposures of the base also occur in the Río Jubones [6814-96305]. The river bed is occupied by the Jubones Formation. This is overlain, unconformably, by about 20 m of andesitic debrites (Santa Isabel Formation). These are in turn overlain by Ayancay Group sandstones. This second surface of unconformity, clearly a paleoslope, dipped gently east. The sandstones onlap towards the west and thicken east.

The formation overlies a complex basement at Shucu [6767-96285], south of the Río Jubones, including a truncated wedge of the Jubones Formation (Figure 7). The formation reappears less than 2 km along strike to the northeast [6781-96293], on the same faultline (Gañarín Belt). There, the fault displacement declines progressively into the unconformably overlying Ayancay Group. The highest few metres of Ayancay strata, best exposed near Zula [7043-96493], comprise landslipped cream mudstones with a thin (4 cm) coal. A mainly Middle Miocene age is indicated by fission track dating of the air-fall tuffs. The youngest age is about 10 Ma (Hungerbühler, in prep.). There are two key areas for demonstrating the age relationships with the Santa Isabel Formation. Along the Girón valley, between [6925-96374] and Girón, there are many places where the Ayancay red-beds are undoubtedly underlain by andesite tuffs, for example the Río Rircay [6999-96442]. The second area is around Tuncay, Asunción and Rambrán. At Tuncay [6904-96467], andesitic tuff-breccias (Santa Isabel Formation) are developed above and below a conglomerate sequence. The red-beds thin, and finally wedge out, northwards. Southwards, they run to Laguna Tablón [6911-96463], but thereafter there are no exposures and between the lake and the Cuenca-Machala road Saraguro Group tuffs are apparently overlain directly by the Santa Isabel Formation.

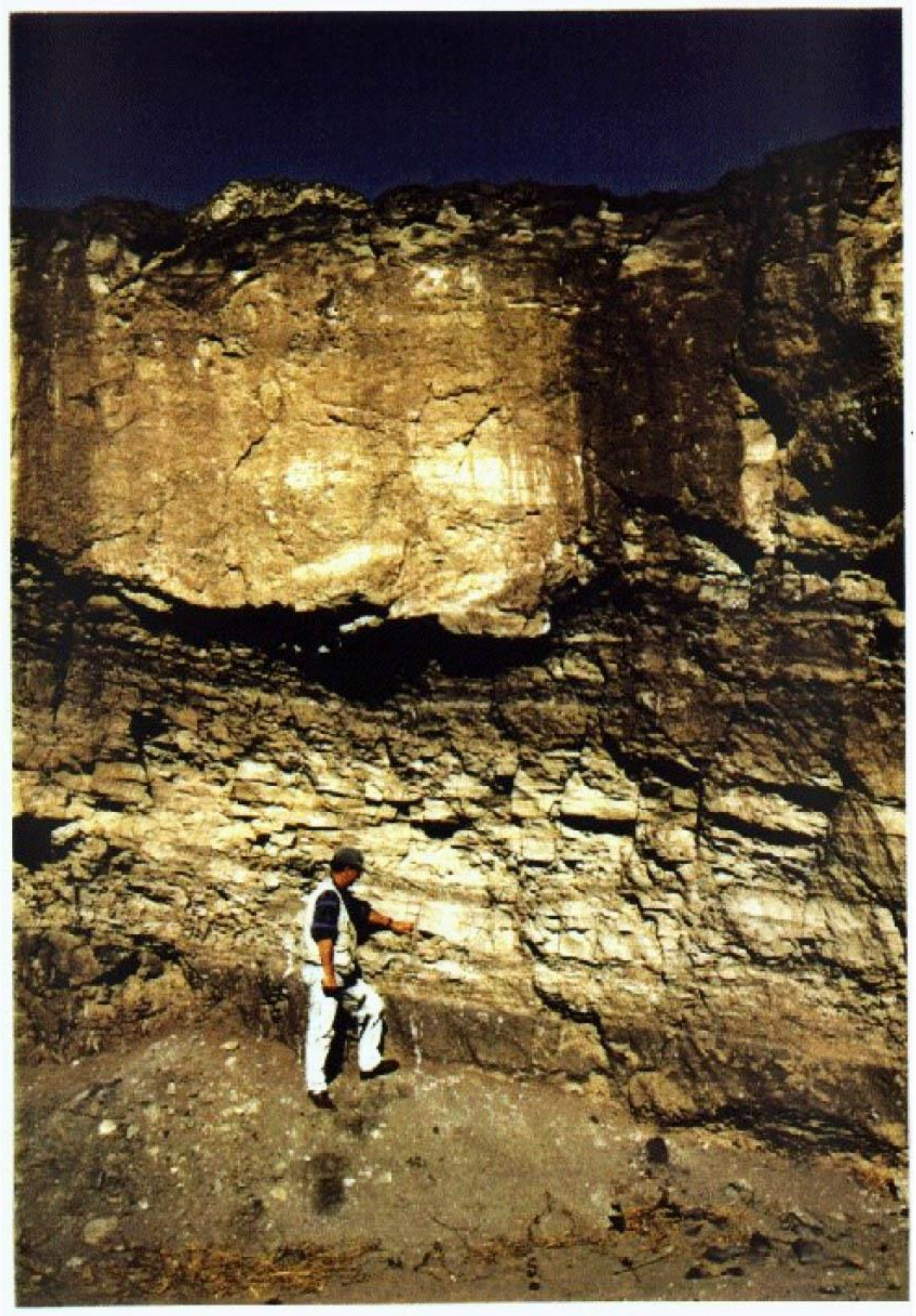

Plate 7. Fluvial sequence. Channelized fine conglomerate to coarse sandstone above sandstones, siltstones and purplish silty mudstones with green reduction spots (at geologist's feet). Ayancay Group [6812-96298]

3.10.1 Interpretation

The Ayancay Group basin, interpreted as an intermontane basin, was probably much larger than the present outcrop. It is certainly linked with the Cuenca Basin and large parts are probably concealed by younger rocks. Initial sedimentation drowned the hills and valleys of the paleotopography and some faults were draped and sealed as sedimentation outstripped faulting. Proximal sediments, close to the basin margins, were alluvial fans. More distal sediments were fluvial. The style of fluvial deposition is uncertain, but the sandstones are largely tabular and continuous, with internal trough cross-stratification. This, and the absence of large-scale point bars, suggests braided systems. Areas which are dominated by mudstones and siltstones may reflect meandering rivers. Temporary lakes and swamps also developed.

The basin appears to have been an asymmetrical half-graben, thickening and coarsening towards a southern hinterland of higher relief (Plate 6a) and with alluvial fans spilling northwards off a southern fault scrap (Girón Fault System). However, because of the huge post-Ayancay uplift and erosion (inversion) to the south, it is difficult to be sure that the basin did not continue farther south.

The sediments were clearly derived from several sources. The paleocurrents (see details) at the north end of the outcrop, between Tarqui and Girón, imply a source region to the west.

Paleocurrents and coarser facies in the south of the Santa Isabel Basin indicate a southern source. In the north, they imply a northern and western source.

The accumulation of a great thickness of red-beds required accelerated subsidence and a change in the tectonic regime at the beginning of the Middle Miocene. The likely controlling faults were the northeast- to north-northeast-striking Gañarín Belt and Girón Fault System. The virtual absence of the Ayancay Group, and the overlying Turi Formation, west of the Gañarín Belt implies that it was an important control. Explaining an extensional regime between the two fault systems, using either the Riedel shear model (Tchalenko, 1970; Tchalenko and Ambraseys, 1970) or transtension, requires a sinistral strike-slip component. However, this may have been very small. Simple east-west extension may have been sufficient to cause a small sinistral strike-slip component on the controlling faults.

3.10.2 Details

3.10.2.1 Paleocurrent data: These come from trough or tabular cross-stratification. The data tend to support the onlapping relationships seen at the base. Localities near the west end of the Santa Isabel Basin, where westward onlapping occurs, show east-directed flow. A locality at Loma Peña Blanca [6843-96322] shows flow towards 115°; domino faulting of the same bed (faults 175/70 E) indicates penecontemporaneous east-west extension. Farther south at Uchucay [6828-96294 and 6819-96298], paleocurrents were towards 006°, 262°, 320° and 340°, indicating southern derivation. Paleocurrents from beside the Girón Fault, at Loma El Quingo [6919-96338], are towards 323° and 312°. Data from between Gigantones [6990-96430] and Tarqui show consistent east- to southeast-directed flow. At Zula [7043-96493], close to the contact with the overlying Turi, flow was towards 157°. Near Girón [7047-96503] it was towards 196°. Tabular and trough cross-stratification around Escaleras [7156-96643] shows flow towards 087°, 140°, 066°, 102°. At Francés Urcu [7169-96674], tabular cross-stratification in four consecutive beds of pebbly sandstones shows consistent flow towards 100°.

3.11 Turi Formation (Erazo, 1957)

This comprises massively bedded, ill-sorted tuffites (tuffaceous boulder beds, conglomerates and sandstones) with a strong andesitic detrital component. Towards the southwest, there is a greater percentage of andesitic tuff-breccias. The formation was defined in the Cuenca Basin by Erazo (1957). The outcrop is restricted to the north of the Girón Fault System and to the east of the Gañarín Belt. It forms the spectacular cliffs [7067-96554] above the Cuenca-Machala road northeast of Girón. In the southwest, the outcrop extends to the Cordillera de San Pablo [6915-96523], above San Fernando (see details section).

The base, a probable angular unconformity, is widely exposed. The formation overlies the Ayancay Group between Zula [7043-96494] and Tarqui. Good exposures of the contact occur west [7162-96672] of Tarqui, where the Ayancay Group is overlain, with mild angular unconformity, by massive conglomerates. These are well-sorted with clasts 4-10 cm in diameter. Andesite, sparse psammite and cherty tuff dominate. West of Girón [7043-96501], the basal beds are grey, massively bedded, very well-cemented boulder beds, conglomerates and coarse feldspathic sandstones. South of Zula, the formation sits on the Santa Isabel Formation. The contact is marked by the change from smooth slopes with limited exposure, to the strongly featured outcrop of the Turi, for example around Balzapamba [6969-96446].

The maximum total thickness is about 1080 m based on a section between Girón and the páramo at Ucshapucará [7040-96558].

A small horst (?) of the Santa Isabel Formation occurs within the Turi outcrop west of Girón. A syn-depositional northeast fault [7026-96512] marks the contact with the Turi Formation. Massive, non-bedded andesitic lavas on the north side are replaced to the south by a much softer sequence, about 240 m thick, of grey sandstones, bright green mudstones, debrites and conglomerates.

Previously considered as Pleistocene (Bristow and Parodiz, 1982), fission track dating demonstrates a Late Miocene age (8-9 Ma) (Steinmann, in prep.).

3.11.1 Interpretation

Sedimentation was dominated by outwash fans of debris-flows, with few primary volcanic rocks. Whether the andesitic debris was derived from andesitic stratovolcanoes or lower relief edifices along fissures is uncertain. However, in RADARSAT images, Quimsacocha has the form of a volcano; and the younger formations dip radially away from the Quimsacocha Caldera. This may reflect doming after deposition, but we believe that the Turi, at least in this area was deposited on the flanks of a volcano, about 40 km across at the base, and that the dips, at least as far as the influence of the Girón Fault System, are much as they were in the late Miocene.

The thickness is very variable, with a large thickness towards Cuenca, Girón and San Fernando, but very thin or absent to the west of the Gañarín Belt. It seems that the volcano sat at the foot of, or astride, a major normal fault (Gañarín Belt), throwing down towards the east, and that an apron of debris spread eastwards. Close to the fault scarp, and to the inferred volcano, there are primary andesite tuffs; farther east, the aspect is entirely sedimentary.

The paleogeography was probably more complex towards the Girón Fault System. Northwest of Girón, a minor horst supplied debris southwards. The axis of the basin was perhaps coincident with the Girón Syncline. Paleocurrent data from north of Girón [7083-96548], and within 1 km of the Girón Fault are towards 257°, 023°, 342° and 344°, implying derivation from the south.

3.11.2 Details

3.11.2.1 Girón and Quimsacocha**:** Extensive exposures of the formation occur between Girón and San Fernando and on the road [6972-96574] to Quimsacocha. The higher rocks are softer and less consolidated, for example in cliff exposures at San Martín [6985-96543 and 6990-96523], but still maintain a strong andesitic component.

East of Quimsacocha the Río Tutupali track has many exposures of very poorly sorted, massive cobble- and boulder rich debrites. Most clasts are pale grey lava or intrusive rock of andesite/dacite composition; they have feldspar phenocrysts of two sizes and sparse amphibole phenocrysts. The boulders are well-rounded and reach 1 m in diameter, for example [7052-96654]. Some are red and oxidised. The matrix of the debrite is decomposed buff/yellow, fine-grained tuff. In the Río San Agustín [7138-96643], similar debrites contain sparse coal fragments in the rotten tuffaceous matrix. There are also some clasts of acid tuff rich in quartz crystals.

***3.11.2.2 Cordillera de San Pablo* [6915-96523]:** These cliffs expose about 600 m of well featured, massively bedded andesitic tuff-breccias, crystal tuffs and fine tuffaceous sandstones. There is undoubtedly a much greater percentage of primary andesite tuff than farther east. Exposures farther north, on the Turupamba road [6891-96551], display green andesitic tuff-breccias, sandstones and fine conglomerates.

3.12 Turupamba Formation (new)

This comprises rhyolitic to dacitic tuffs, with common pumice lapilli, and tuffites. It crops out only on the páramo west of San Fernando. It overlies the Turi Formation and appears to be overlain by the Quimsacocha Formation. It wedges out eastwards and the other two formations come together.

The base, exposed in the road above Turupamba [6886-96558] is marked by distorted, folded and brecciated fine tuffaceous sandstones or tuffs (?) with sparse coal fragments. The rocks are well-bedded and strongly pyritized (see Section 6.5). Vaguely bedded acid tuffs occur slightly lower down the track. They are strongly clay-altered.

The formation is about 360 m thick, but only the lower 200 m have been examined. These comprise acid tuffs, mainly 2 to 20 m thick, giving the outcrop a well-featured appearance, for example Laguna Habacota [6866-96575]. In detail, the tuffs are massive and dacitic, with common green pumices and quartz crystals. Coal fragments and disseminated pyrite are features of some. Locally [6856-96557], the tuffs are very thinly bedded. A prominent bed of coarse tuff-breccia, about 5 m thick, occurs just west of Tres Lagunas [6846-96562]. It comprises tightly packed fragments, up to 0.5 m in diameter, of acid tuff, flow-foliated rhyolite and chilled porphyritic andesitic lava/intrusive rock. It can be traced for about 1.5 km along strike. Some of the acid tuff clasts, crammed with quartz, feldspar and biotite crystals, closely resemble the Jubones Formation.

The highest part of the formation, which caps Loma Habacota [6868-96573] and the páramo around [9870-96530], has been seen only with binoculars, and seems to comprise much thicker, more massive units of tuff/lava (?).

3.12.1 Interpretation

The formation is the product of numerous minor rhyolitic/dacitic ash-flows, none of them representing major eruptions, interspersed with periods of fluvial and lacustrine sedimentation.

3.13 Uchucay Formation (DGGM, 1973b)

This sequence of yellow conglomerates and boulder beds, with a very mixed assemblage of local rock types, is confined to the Santa Isabel area and mainly overlies the Ayancay Group with strong angular unconformity (Plate 6b). The maximum thickness is probably 100m. In some places, the unconformable base truncates large scale folds in the Ayancay Group, for example Hacienda Uchucay [6825-96300]. The formation was assumed to be Pliocene, but a new fission track date gives 9.4 ± 0.8 Ma (Late Miocene) (Hungerbühler, in prep.).

3.13.1 Interpretation

The formation is probably a proximal alluvial fan sequence, spilling off fault scarps. The fission track date is important because, taken with the 10 Ma maximum age of the Ayancay Group, it precisely fixes the compressional deformation along the Girón Fault System (Section 5).

3.14 Quimsacocha Formation (new)

This comprises fresh andesite lavas, commonly flow-foliated, and pyroclastic andesitic tuff-breccias. The lavas are grey and well-jointed with flow-aligned feldspar phenocrysts (e.g. WP-352A). In most exposures, they weather spheroidally. The formation occurs only around, and within, the Quimsacocha Caldera. It caps the Turi Formation in the east and south. The minimum thickness is 160 m. The base is very obvious, and sharp, in the road [6970-96583] to Quimsacocha. There, the cliffs of the softer, more easily eroded, Turi Formation are overlain by flatter ground which rises steadily and gently towards the caldera rim. Measured flow foliations consistently dip gently (5°) away from the caldera. Locally [6923-96652], the ground is littered by rounded boulders, several metres in diameter, with distinctive bread crust outer surfaces. They probably budded off lava flows or domes and rolled. Exposures of andesite lava and andesitic pyroclastic breccia occur within the caldera [6979-96636 and 6981-96634].

The formation is inferred to overlie the Turupamba Formation to the west, but the critical area has been seen only with binoculars. The age relationship with the Tarqui Formation is not known because the lavas wedged out before the first exposures of Tarqui.

3.14.1 Interpretation

The andesites are interpreted as proximal products of the Quimsacocha stratovolcano.

3.15 Tarqui Formation (UNDP, 1969g)

This comprises mainly poorly consolidated rhyolitic tuffs and tuffites (conglomerates, sandstones, mudstones) rich in quartz. It has been mapped only in the east, around Saraguro and on the east flank of the Quimsacocha volcano. The strata are flat-lying. An angular unconformity at the base is very clear west of Saraguro, around San Pablo de Tenta [6908-96026], where horizontal beds overlie Saraguro and Sacapalca strata which have greater than 20° dips. The maximum thickness, west of Saraguro, is about 400 m.

A distinctive yellow or buff, rhyolitic lithic lapilli-tuff, at least 160 m thick, forms much of the outcrop around Saraguro. It comprises a gritty sandy matrix, rich in angular lithic fragments, quartz, feldspar and biotite, with evenly scattered, matrix-supported, angular fragments, 10 to 50 mm long, of andesite and quartz crystal-rich welded tuff. A weak bedding-parallel alignment of pale green clasts, possibly pumice, is apparent. In a 1.5 km-long roadcut [6955-95985], vague beds, defined by changes in clast size, are apparent. The rock is probably a non-welded pyroclastic tuff, but unusually crystal-rich. A spectacular exposure of the same tuff occurs near the pre-Inca hillfort at Jera [6949-96033]. Silicified Saraguro tuffs, resembling rhyolite, are overlain by 3 m of clast-supported breccia of the same material, interpreted as a paleoscree, and then by over 50 m of the lithic lapilli-tuff. The base of the tuff is covered by large tree imprints.

Other important components around Saraguro are coarse conglomerates and boulder beds. Good exposures occur in the Saraguro-Selva Alegre road [6947-95999]. Rotten lithic tuffs are underlain by at least 40 m of decomposed, coarse conglomerates of alluvial fan aspect. The clasts are mainly well-rounded, quartz-, amphibole- and biotite-rich crystal tuffs and andesites.

Outliers occur between Oña and Saraguro. At Cerro Zhio [7024-96137] about 140 m of strata overlie the La Paz Formation. A quarry displays about 25 m of massive- to thinly-bedded white and pale green coarse sandstones, fine conglomerates and air-fall tuffs. Large scale cross-stratification, with dune bedforms of >1 m amplitude, gives paleocurrents towards 009°, 008° and 160°. Plant fragments occur on the foresets. Rootlets occur in white tuffaceous mudstones. Nearby exposures [7035-96114] comprise only massive- to thinly-bedded, rotten-weathered acid tuffs and tuffites. Near Carboncillo [7030-96100], which probably takes its name from coal within the Tarqui, there are further exposures of sedimentary rocks including mudstones, coarse sandstones and fine conglomerates. They are all thinly bedded. Detrital magnetite and plant remains are common.

A flow-foliated glassy, pink and green striped, aphyric rhyolite, about 40 m thick, occurs south of Carboncillo [7025-96061]. The sub-horizontal flow foliation is overprinted by numerous siliceous nodules, 5-25 mm in diameter. In thin section, the fresh glass matrix is overprinted by radiating devitrification chlorite rosettes (WP-494). It is unclear whether the rhyolite belongs to the Saraguro Group or the Tarqui Formation, but its freshness suggests the latter.

The acid tuffs east of Quimsacocha cap the Late Miocene Turi Formation, apparently conformably. Large dacite stocks, which invade the formation south of Saraguro [6941-95954], are dated at 9.6 ± 0.5 Ma (Late Miocene, Appendix 1), giving a minimum age for the Tarqui of approximately 10 Ma. This suggests that the Turi and Tarqui formations may be partly contemporaneous.

3.15.1 Interpretation

The formation represents a mix of primary acid ash-flow and sedimentary activity. A relatively low relief plain is envisaged, with meandering rivers, lakes and swamps. There is much evidence, mainly plant material, of deposition in terrestrial conditions. These were inundated periodically by air-fall and ash-flow tuffs.

4. INTRUSIONS

Two main types of intrusion are recognized: coarse-grained granitoids and sub-volcanic minor intrusions. Granitoids intrude the metamorphic rocks, the Cretaceous formations and the lower structural levels of the Saraguro Group and Sacapalca Unit. In younger strata, most intrusions are fine grained. There was a distinct phase of plutonism between 16 and 19 Ma (Early Miocene). Given that the K/Ar ages are cooling ages, this plutonism may have been broadly contemporaneous with the major ash-flow episode at the top of the Saraguro Group. Thin section and geochemical analysis indicate that the K-content of the granitoids is low. Potassic feldspar is rare and the rocks are generally tonalites.

4.1 Granitoids

4.1.1 Paccha-Cordoncillo

The largest outcrop of this composite granitoid intrusion occurs west of Paccha and is extensively exposed on the Pasaje road. It is an irregular-shaped intrusion, with an outcrop of greater than 150 km2. It comprises two main phases: an extensive granodioritic one and a dioritic to gabbroic phase. The latter, which is characterised by a mineralogy of coarse equigranular plagioclase, amphibole, a little biotite and minor quartz, is often foliated and, locally, has been previously interpreted as a hornblende-gneiss or amphibolite of the metamorphic basement, windows of which are present to the north of Cordoncillo [6500-96050].

In the main pluton, there is some evidence of chilling and rapid emplacement to high level because the plagioclases are zoned and there is a much finer, though holocrystalline, interstitial matrix (WP-1600). The chemistry of the single analysed sample is tonalitic (WP-1600; Appendix 2). A K/Ar date of 16.89 ± 0.16 Ma, interpreted as an intrusive age, comes from Paccha [6471-96060] (Appendix 1). The youngest rocks it intrudes are Saraguro, dated at 21.5 ± 0.8 Ma near Zaruma.

4.1.2 San Lucas and Fierro Urcu

The San Lucas intrusion, emplaced mainly into metamorphic rocks of the Cordillera Real and the Sacapalca Unit, occupies the Santiago to San Lucas area. A series of K/Ar dates of about 60 ± 5 Ma (Palaeocene) and a Rb-Sr isochron age of 53 ± 2 Ma were obtained by Aspden et al. (1992). The intrusion appears to be physically linked with the granodiorite exposed to the west at Fierro Urcu [6860-95897], but the latter intrudes post-23 Ma Saraguro Group strata at Fierro Urcu. It is therefore much younger. Thus, either the Paleocene age of the San Lucas pluton is incorrect or, more likely, there are two separate phases of intrusion represented by the mapped pluton.

4.1.3 Shagli

Because of the erosion level, there are very few major intrusions unroofed in the northeastern half of the field area. An exception is at Shagli ("Shaglli"). This truncates the Jubones Formation and has been dated at 17.64 ± 0.61 Ma (Early Miocene) (WP-233; Appendix 1). It is a composite intrusion, comprising mainly coarse granodiorite with subordinate micro-granodiorite, microdiorite and pegmatite. A microgranodiorite dyke intrudes coarse-grained granodiorite (feld + amph + bt + qtz) at [6795-96512]. A 2 m-wide pegmatite pod at [6793-96520] comprises clear quartz and tourmaline.

4.1.4 Ponce Enríquez to Uzhcurrumi

In this area there are many granitoid outcrops. K/Ar dates of between 9 and 12 Ma are available for the mineralized granodiorite/tonalite batholith of Chaucha, to the north of the district (Bristow and Hoffstetter, 1977; Kennerley, 1980). This continues into the field area at Tenguelillo [6610-96610] and in the Río San Miguel [6590-96670]. Around Uzhcurrumi, there are poorly exposed windows of granitoid at San Sebastián [6637-96353], La Tigrera [6512-96446] and Uzhcurrumi [6539-96326]. All are granodiorites, although the mineralogy is variable, with different proportions of biotite and amphibole. A large quartz diorite northeast of Uzhcurrumi [6635-96347] has been dated at 19.92 ± 0.18 (Early Miocene) (Appendix 1). The rock comprises hornblende, biotite, plagioclase and quartz; the plagioclases have chloritized (melt?) inclusions (WP-14; Appendix 2). The probable extension of this body follows the Río Jubones towards San Sebastián [6635-96350].

4.2 Sub-volcanic/minor intrusions

Sub-volcanic intrusions, locally breaking out as domes (Section 4.3), occur mainly in the Saraguro Group and Santa Isabel Formation. They are concentrated in the Gañarín Belt, a belt of faults, intrusions (rhyolite and andesite stocks) and hydrothermal alteration (Section 6.2) (Figure 5). The component intrusions of the Gañarín Belt are described, from south to north, in the details section.

A series of high-level andesite/dacite (?) intrusions occur south of Cumbe. A road exposure at [7198-96473] is pale grey and massive with common feldspar and biotite, and sparse quartz, phenocrysts. In thin section (WP-323), feldspar microlites define a flow foliation in a glass matrix.

The youngest dated intrusions (9.6 ± 0.5 Ma; Appendix 1) occur immediately south of Saraguro. They are very large porphyritic dacite stocks up to 2.5 km in diameter. The rock is generally decomposed, pale grey and soft. It has a pinkish, very fine-grained matrix with abundant large (3-8 mm) plagioclase, oxidised biotite and sparse quartz phenocrysts. The plagioclases are strongly zoned (WP-653).

4.2.1 Gañarín Belt details

***4.2.1.1 Zaruma*:** At the southern end of the belt, at Zaruma, the Saraguro Group is intruded by orange-weathered, irregular rhyolite stocks (Section 6.4). The largest crops out between Zaruma, in the southeast, and Loma La Cuchilla [6495-95974], in the northwest. It narrows from about 2.5 km wide at Zaruma, to about 0.5 km at La Cuchilla. At La Cuchilla it follows the regional strike and appears to dip westwards, concordantly with Saraguro tuffs. It may therefore be a sill.

***4.2.1.2 Río Pilincay*:** A stock or dome [6644-96103] on the Chilla/Manú watershed comprises purple/green striped, strongly flow-banded and locally silicified rhyolite, with vugs of chalcedony. It has quartz, plagioclase and biotite phenocrysts. In thin section, it shows snowflake devitrification of glass (WP-725).

4.2.1.3 Río Ganacay to Abañín [6699-96306]: This large, irregular rhyolite is strongly flow-banded and is emplaced, with steep contacts, against clay-altered andesites. The outer 10 m have also suffered strong clay alteration. The rhyolite has a bright green/purple striping, with common nodules up to 10 mm in diameter. In thin section, it is glassy, with scattered plagioclase and amphibole phenocrysts and large zircons (WP-782). The matrix and phenocrysts are partly silicified and the glass is overprinted by radiating devitrification (chlorite). A sample from the same intrusion [6686-96316] is an obsidian with identical phenocrysts (WP-1047). Possibly, this intrusion broke out as a dome, because it sends off a flat-lying branch towards Abañín [6675-96316]. The body does not extend into the overlying Santa Isabel Formation, indicating that it is probably pre-18 Ma.

***4.2.1.4 Pachagmama*:** This irregular, vertical-sided rhyolite is the largest intrusion in the Gañarín Belt. It is interpreted as one of the post-collapse intrusions of the Jubones Caldera (Section 3.8.5). It was dated by K/Ar whole rock at 26.8 ± 0.7 Ma (Kennerley, 1980; Appendix 1), although we believe it to be younger because it intrudes the Jubones Formation (dated at 22.76 ± 0.97 Ma by K/Ar on biotite). It is an extremely tough, buff coloured rhyolite with very few plagioclase phenocrysts. Fine columnar jointing is common on the east side [6748-96319]. Flow banding is strongly developed, largely striking northeast and dipping moderately northwest. Spectacular flow folds occur at the Virgin shrine [6719-96323], where clay-altered and silicified rhyolite is in contact with silicified tuff.

South of the Río Jubones, the Pachagmama intrusion sends off a dyke, ca. 200-300 m wide. Near San Sebastián de Yuluc [6729-96292], on the inferred outcrop of the dyke, there are abundant boulders of rhyolite breccia. Identical breccias are exposed in situ along the east flank of the Pachagmama intrusion [6765-96327]. The breccias developed either by mechanical deformation of the columnar jointed rhyolite or by hydraulic fracturing (cf. Phillips, 1986). The dyke swells into a body about 1.5 km wide at Cuchicorral, west of San Sebastián de Yuluc [6720-96279]. This mineralized orange-weathered rhyolite is brecciated on the east side, and weakly flow-foliated (042/42 N) elsewhere. It is locally feldspar-phyric.

***4.2.1.5 Río Jubones to Paquiloma*:** Other small rhyolite intrusions, only a few hundred metres in diameter, occur in the Río Jubones [6785-96307] and Loma Paquiloma [6767-96378]. In the latter, rhyolite bodies occur within the lower tongue of the Santa Isabel Formation. They are strongly foliated and silicified. A thin section from Paquiloma (WP-208) shows foliated glass affected by perlitic fractures along which there is slight devitrification. Immediately east of Paquiloma, rhyolites are also incorporated as large loose blocks, 10-15 m in diameter, within the andesitic breccias of the Santa Isabel Formation. This implies that some broke through the surface to become extrusive or that eroded/collapsed domes were emplaced into the Santa Isabel Formation.

***4.2.1.6 Dandán*:** A rhyolite with identical characteristics to Pachagmama, including clay-alteration and sulphide enrichment, occurs at Dandán [6816-96375]. The rhyolite is foliated (154/90) and in thin section displays flow-aligned plagioclase microlites with scattered plagioclase and quartz phenocrysts (WP-191).

***4.2.1.7 Cañaribamba to Tuncay*:** After Dandán, andesite intrusions follow the Gañarín Belt northeastward, with intrusions at Yiripato [6833-96395], Cañaribamba [6855-96420] and Tuncay [6900-96475]. They become younger northwards. The Tuncay intrusion cuts the Ayancay Group and the upper tongue of the Santa Isabel Formation, making it younger than 14 Ma. A thin section (WP-326) from Tuncay [6909-96476] comprises a fine crystalline groundmass with large strongly zoned plagioclase phenocrysts (An55) and pale pink augite with finer augite rims. The Yiripato intrusion comprises two distinct size fractions of plagioclase phenocrysts. The glassy groundmass testifies to rapid chilling and high-level emplacement.

***4.2.1.8 Tres Lagunas*:** Close to the Gañarín Belt, the Turupamba Formation (post-Late Miocene) is intruded by several large stocks of porphyritic andesites. At Tres Lagunas [6862-96553] a grey andesite stock, 2 km long and about 0.5 km wide, comprises amphibole and plagioclase phenocrysts in a very fine-grained holocrystalline matrix (WP-304). The rock is very fresh.

***4.2.1.9 Quimsacocha*:** The Quimsacocha Caldera is invaded by two varieties of rhyolite, one of which is undoubtedly intrusive. A large aphyric rhyolite intrusion, probably less than 5 Ma old since it invades the topographically distinct, only slightly eroded caldera, occupies the east and north sides. It apparently intrudes the ring fracture. A second large body of similar rhyolite, with a north-northeast strike, cuts across, the caldera ring fracture in the southwest corner [6947-96627]. The other important element within the caldera is a quartz-phyric rhyolitic lava or intrusive rock. A weak, sub-horizontal foliation at [6978-96657] suggests lava. It is white-weathered and outwardly appears clay-altered. However, in thin section it is remarkably fresh, with unaltered quartz, plagioclase, amphibole and biotite phenocrysts in an almost glassy flow-foliated matrix (WP-375). The rhyolitic lava appears to be overlain by andesitic lavas and andesitic pyroclastic breccias (Santa Isabel Formation) in a road section within the caldera [6979-96636].

4.3 Domes

In some cases, the sub-volcanic intrusions probably emerged as domes. The most striking example overlies the Jubones Formation in the Pucará road [6726-96407]. This deposit, up to 300 m thick, has a lenticular, broadly bedding-parallel form and persists along strike for about 5 km. It is a massive, rubbly weathering rhyolite breccia, pink and intensely silicified, with some chalcedony-lined vugs. The matrix is locally foliated, bands emphasized by variable silicification or recrystallization. It contains sparse crystals of heavily embayed quartz, feldspar and rare biotite. Locally, it is glassy and obsidian-like. Blocks of flow-banded rhyolite, up to at least 4 m in diameter, are widespread. In thin section, the nature of the matrix is difficult to determine because of the silicification. However, large quartz-replaced shards suggest the rock is partly pyroclastic (WP-172). Compositionally, the rock resembles the Jubones Formation, although depleted in crystals, and it may have shared the same high-level magma chamber.

5. STRUCTURE

The field area contains several important fault systems (Figure 1). Regional folding, other than minor tilting, is very localized in the Tertiary strata and most of the folds that do exist are related to syn-depositional pulses of activity on the faults (Figures 4, 8). For example, the Jubones Formation (Early Miocene) is involved in some major folds, such as La Cría and Yaritzagua, but horizontally truncates other folds, such as Pedernales and Narihuiña. Because of the mineralization aspect, the Gañarín Belt, and the serpentinite-filled Río Chico Fault, are discussed in Section 6.

5.1 Chaucha-Río Jerez Lineament

This north-northeast belt of faults and inliers of metamorphic rock (Dunkley and Gaibor, 1997; Misión Belga, 1989c) can be traced south from the Chaucha area to the San Pablo de Cebadas Inlier. The west side of the inlier is a west-verging reverse fault which brings up the Bella Rica Basalts of the Pallatanga Unit. Farther south, it is not clear if the lineament runs into the La Tigrera Fault or into a belt of anomalously steep, east-dipping acid tuffs (Narihuiña tuffs; Table 1) which runs from Gramalote [6550-96350] near Uzhcurrumi, through the gold prospects of Gigantones [6596-96470] and Tres Chorreras [6634-96503], to Narihuiña. Around Narihuiña [6659-96546] the strata are locally vertical. The Jubones Formation, which crops out a short distance to the east, is inferred to overlie the steep strata with strong angular unconformity. This is based on the evidence from Pedernales [6835-96603], where it truncates an asymmetrical anticline in the Narihuiña tuffs. The major tilting was clearly post-28 Ma, the depositional age of the Narihuiña tuffs, and pre-23 Ma since neither the La Fortuna nor Jubones Formations were affected. A major phase of deformation therefore occurred on the southern extension of the Chaucha-Río Jérez Lineament in the Late Oligocene.

5.2 Girón Fault System

This important belt of faults and tight folds is still active (Plate 8a). It runs between Cuenca and El Cisne, swinging from a north-northeast strike near Cuenca, to a north strike near El Cisne. Thrusts, not previously recognized, are an important component, explaining anomalies in the stratigraphy. Because they are difficult to recognise, it is likely that their number has been underestimated.

The Girón Fault was modelled as a normal fault, with downthrow to the northwest (DGGM, 1974; Winter et al., 1990). It is true that there is a present downthrow to the northwest on the active Girón Fault, but we believe the fundamental fault structure is southeast-dipping and reverse. Exposures east of Santa Isabel [6919-96338], show that the fault, which juxtaposes the Jubones Formation and Ayancay Group, is west-verging and reverse. Slickensides pitch vertically, supporting dip-slip. Furthermore, Sacapalca strata are thrust over the Santa Isabel Formation and Ayancay Group at La Cría [6905-96270] (Plate 10). This west-verging structure must indicate post-10 Ma (Late Miocene) compression and the evidence from the Uchucay Formation (Section 3.13) indicates deformation at ca. 10 Ma. Fold style along the Girón Fault System also supports reverse movement. The La Cría Anticline (Plate 8b) and complementary Yaritzagua Syncline are strongly northwest-verging, with locally vertical northwest limbs (Figures 4, 8b).

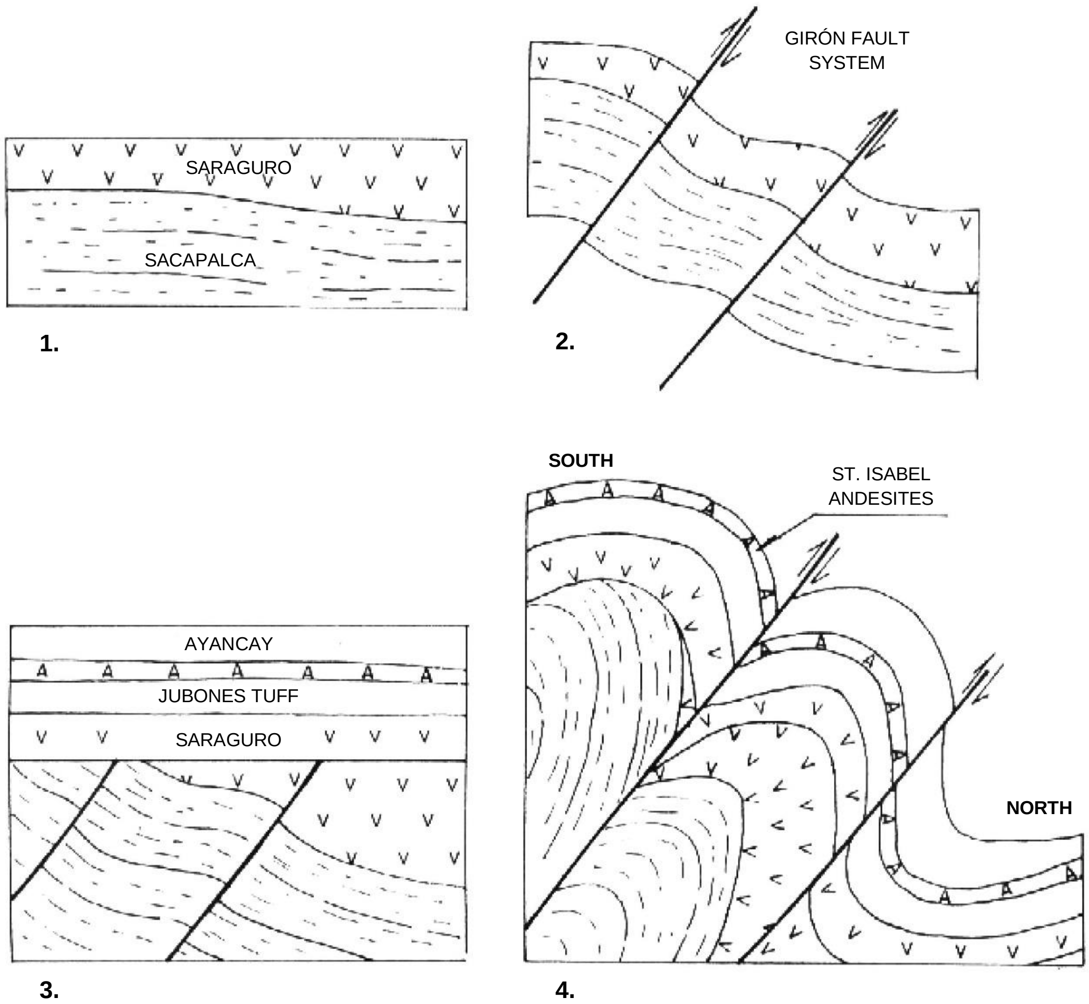

Figure 8. Cartoons showing the development of the angular unconformity in the La Cría Anticline, within the Girón Fault System.

1. Pre-23 Ma (approximately the Oligocene/Miocene boundary)

2. About 23 Ma

3. About 14 Ma (Middle Miocene)

4. Present day

Plate 8a. The active portion of the Girón Fault. The zigzag line running the width of the view marks the active scarp. Vegetation is displaced. Above, the horizontal strata are Saraguro acid tuffs, beneath the Jubones Tuff. Taken from about [6897-96386]

Plate 8b. Cliff exposure (800 m high) of the La Cría Anticline from [6895-96257]. The Jubones Tuff is marked by white soils in the middle, sunlit ground at left and at the sunlit crest of the anticline. The La Cría travertine deposit is marked by the large white road cuts in the middle foreground

A strong angular unconformity is visible within the La Cría Anticline (Plate 8b). The Jubones Formation, and a few older tuffs, lie with strong angular unconformity on older Saraguro strata. Figure 8 attempts to explain the unconformity by uplift along the Girón Fault System, with the southern area tilted, by compression and eroded prior to deposition of the Jubones Formation. This would explain the dramatic reduction in the total thickness (to about 1 km) of the Saraguro Group towards the southeast (Oña, Nabón).

At the southern end of the Ayancay Group outcrop [6828-96197], the westward-verging thrusts of the Girón Fault System converge with the eastward-verging thrusts of the Jubones Fault System. Farther south, the thrusts of the now-combined fault system seem to be east-verging, bringing up an inlier of the Yunguilla and metamorphic rocks at Manú (Sections 3.1, 3.4).

5.3 Catamayo Fault

This juxtaposes the Sacapalca Unit and the metamorphic rocks of the Cordillera Real. It was described as the boundary fault of the Sacapalca-Cariamanga-Huancapamba graben by Kennerley and Almeida (1975a) and Baldock (1982), but there is no real evidence, such as sedimentary wedges or fan deposits, to support this. The structure is a west-verging reverse fault in the Catamayo-Loja road [6857-96597], thrusting strongly sheared graphitic phyllites over the Sacapalca Unit and Catamayo Formation. Farther north, the fault is steeply west-dipping and more like the normal, graben boundary, fault envisaged by Kennerley and Almeida (1975a). At Cera [6908-95683], strongly disrupted and sheared, calcite-veined andesites of the Sacapalca Unit are faulted against buff flaggy psammites. About 800 m farther north [6910-95690], a small wedge of graphitic phyllite, a few metres long, is caught up within the andesites at the faulted contact with psammites.

5.4 Piñas-Portovelo Fault System

This important east-southeast fault/thrust has a large downthrow to the north, separating Saraguro Group strata from the El Oro metamorphic complex. Amphibolites are common at the contact. The offset of the Saraguro Group west of Zaruma, indicates vertical displacement of at least 3 km between Piñas and Zaruma.

West of Piñas, the fault appears to be steep. However, between Piñas and Salatí [6636-95847] it is a north-dipping, south-verging thrust. This geometry is most apparent on Cerro La Chuva [6500-95893] where a dacitic tuff of the Saraguro Group is thrust southwards over the metamorphic rocks. Exactly the same happens at Loma Ojeda [6587-95860], southeast of Portovelo. Probable backthrusts also occur. For example, near Piñas [6478-95914] a north-verging thrust (140/36 S) is exposed. It emplaces a 5 m band of amphibolite, and a much greater thickness of granitic gneiss, over a dacitic tuff of the Saraguro Group. The eastward extension of the fault is inferred as far as Payana [6763-95877], northwest of Gualel, where it links with the Girón Fault System. Again, it juxtaposes Saraguro Group strata with the metamorphic rocks to the south.

Plate 9a. The Río Manú Thrust at the Río Manú [6819-96225]. The pink/white soft ground is the Ayancay Group. Nearly vertical bedding is visible at the skyline.
The green rounded slopes to the right are Sacapalca andesites, thrust over the Ayancay Group with vergence to the left (east)

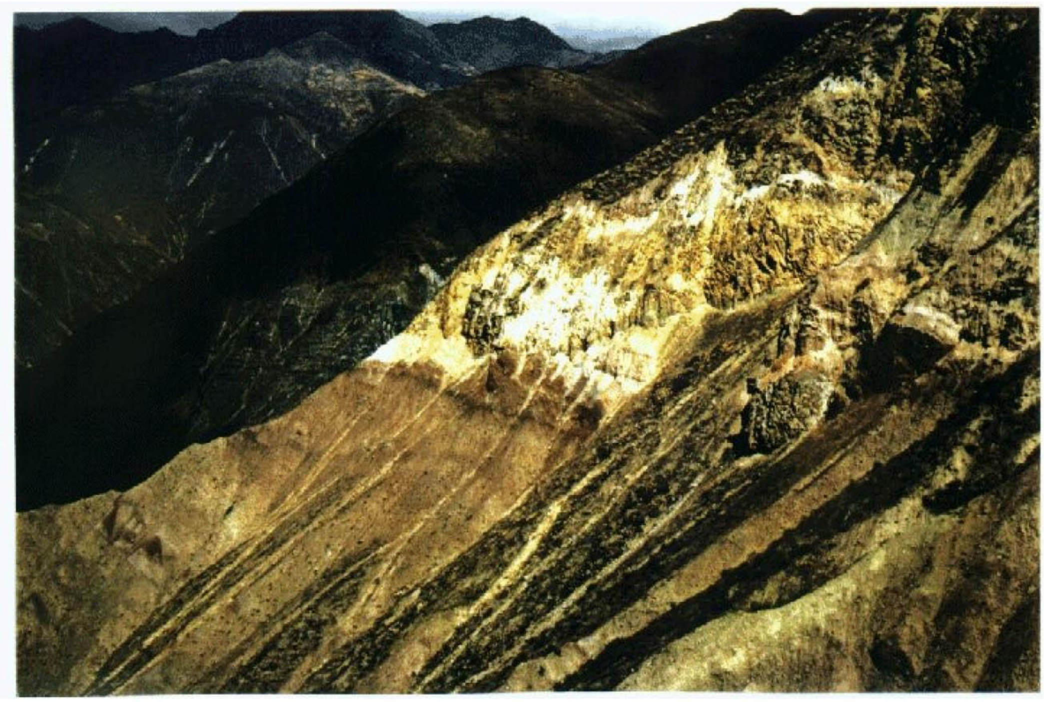

Plate 9b. The Río Manú Thrust at Huayraloma [6823-96241]. The pink strata are overturned Ayancay red-beds. The massive white cliffs are the overturned Jubones Tuff (lowest Miocene), thrust over the red-beds with vergence towards the viewpoint (east)

5.5 Jubones Fault System

This east-striking system juxtaposes the Bella Rica Basalts of the Pallatanga Unit with the El Oro metamorphic complex. Along much of its length it is interpreted as a north-verging reverse fault or thrust. There is also evidence of sinistral strike-slip.

There is much quartz veining and boudinage of psammitic schists along the fault system and the Bella Rica Basalts are strongly brecciated. The width of the disruption, several hundred metres, suggests that the movements were significant. The foliation in the schists strikes east-west, parallel with the fault, and dips south very steeply. Away from the fault, along the Chilla road, the foliation is gentler and has a much more varied strike. The steepening of the foliation towards the fault trace may reflect rotation into the fault.

There are also small-scale indications of strike-slip. Conjugate kink bands in schists at Ducos [6426-96334] give a σ_1 direction of 058°. Nearby [6469-96332], schists with pods of psammite have a steep foliation (080/73 S) which is affected by two sets of structures: a set of asymmetrical ductile crenulations (062/90), with sinistral offsets, and a set of more brittle, hence later, kink bands (average 135/70 S), also sinistral. The kink bands support sinistral displacement on the Jubones Fault System. The crenulations are more difficult to interpret, but the small angle between them and the schistose foliation also support sinistral strike-slip on the fault.

The Jubones Fault System swings southwards at Uzhcurrumi. In the Río Chillayacu [6595-96294] it forms the contact between the Santa Isabel Formation and the Sacapalca Unit and metamorphic rocks. It has a minimum downthrow to the north of 1 km and is interpreted as a north-verging reverse fault. Farther east, the fault develops into a north- and east-verging thrust belt which brings the Saraguro Group and Sacapalca Unit over the Ayancay Group. Thrusts, with tight footwall synclines, are superbly exposed in the semi-desert area where the Río Manú joins the Río Uchucay (Plates 9a, b). In the Río Manú [6814-96227], andesites of the Sacapalca Unit are thrust eastward over the overturned Jubones Formation and Ayancay Group. The perfectly exposed thrust (174/26 W) comprises 0.2 m of gypsum-veined microbreccia. It separates gypsum-veined andesites from greenish, propylitically altered acid tuffs (Jubones Formation). The tuffs have a cataclastic foliation, parallel to the thrust, which overprints a welding foliation. In thin section, the glassy matrix is chloritised and the large plagioclase crystals have suffered brittle grain size reduction (WP-619). Sliding has occurred along the biotites, so that they are much longer and narrow than normal. Northward-verging recumbent folds and overturned strata occur along the southern fringe of the Ayancay Group outcrop [6766-96277 and 6778-96276], close to the inferred thrust(s).

6. ECONOMIC GEOLOGY

The principal mines and prospects within the 3°-4° S sector of the Western Cordillera, are indicated on the accompanying 1:200000 scale geological map, and on the 1:1000000 scale tectono-metallogenic map of Ecuador (BGS-CODIGEM, 1993b). At least five styles of metalliferous mineral occurrence are recognized.

a) Porphyry and stockwork mineralisation associated with rhyolite or andesite (microdiorite) stocks with typically extensive alteration halos.

b) Epithermal deposits associated with eruptive centres, regional fractures and structurally-controlled rhyolite emplacements.

c) Mesothermal polymetallic veins and breccias.

d) Multiple phase occurrences hosting mesothermal polymetallic assemblages, with later epithermal (often highly auriferous, base-metal poor) overprints.

e) Volcanogenic massive sulphides. Example: San Fernando (UNDP, 1969a).

This classification is somewhat artificial, as many individual occurrences display features characteristic of more than one defined category. For example, high-level epithermal overprinting of mesothermal assemblages may, in some instances, have resulted from strong erosion (or simply the prevalence of a very steep geothermal gradient) during the life-span of a hydrothermal system. Thus, at Portovelo epithermal Au veins occur alongside base-metal rich mesothermal vein swarms. At Tres Chorreras, parts of a predominantly mesothermal system display epithermal characteristics. With respect to geographic distribution, the deeply eroded slopes of the Western Cordillera generally host higher temperature, tourmaline-rich, polymetallic mineralisation. In the high páramo auriferous epithermal systems predominate.

6.1 Porphyry mineralisation

The term porphyry-style mineralisation is applied generically to deposits associated with sub-volcanic intrusions and characterized by disseminated sulphides or stockworks within the intrusive facies and surrounding country rocks. Examples of discrete porphyritic stocks occur at Gaby [6428-96620] and Fierro Urcu [6830-95916], and observations made during geological mapping of the 3°-4°S sector of the Western Cordillera indicate potential for additional porphyry-style mineralisation in other areas.

6.1.1 Gaby

At Gaby, east of Ponce Enríquez, an irregular porphyritic microdiorite stock approximately 1 km in diameter intrudes fractured basalts and hyaloclastites of the Pallatanga Unit. The intrusion lies on the eastern side of a topographically conspicuous circular structure some 3 km in diameter, although there is a little additional field evidence of a ring fracture because of the intensity of alteration and weathering. An extensive zone of argillic alteration and tourmalinisation is evident, with Mo-Cu-Au mineralisation present in stockworks and disseminations (Gemuts et al., 1992; Paladines and Rosero, 1996).

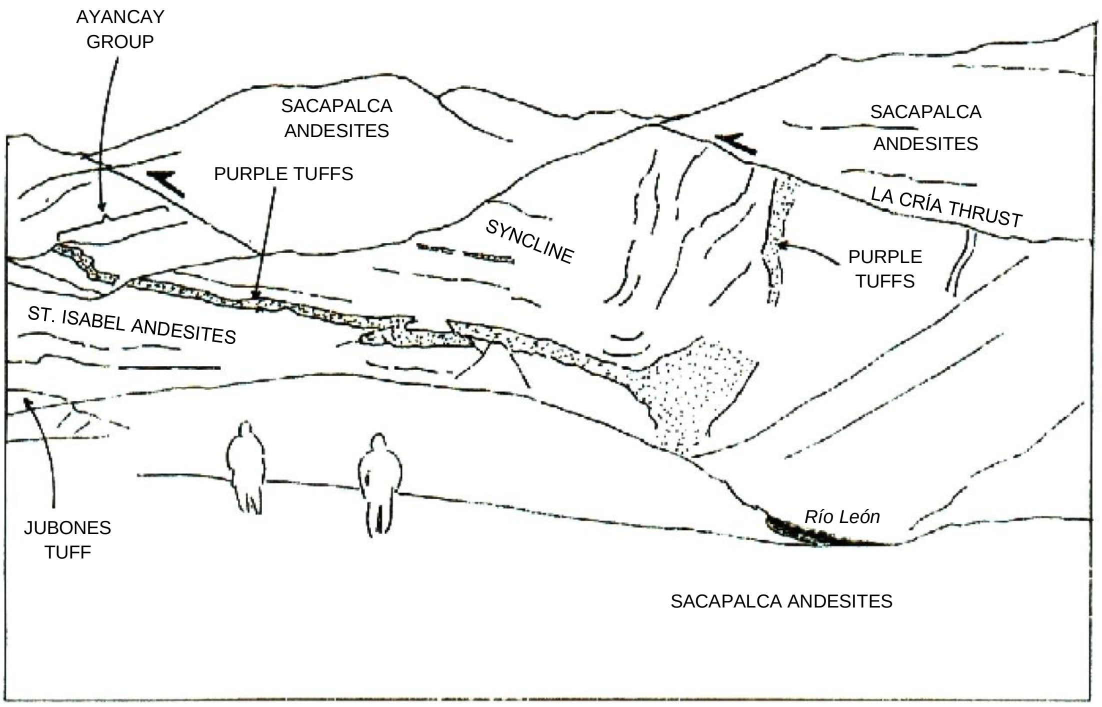

Plate 10. View northwards from Filo de Seucer (foreground) [6877-96210] towards the Río León. La Cría lies slightly to the left of the photograph. The rock face displays a major footwall syncline beneath the La Cría Thrust

6.1.2 Fierro Urcu

Porphyry-style mineralisation at Fierro Urcu, south-west of Saraguro, is associated with a complex of sill-like granodiorites and microdiorites, apparently cut by a younger rhyolite stock (Spindler and Herrera, 1959), within Saraguro Group and Sacapalca Unit host rocks. The granodiorite is extremely variable in texture and appears to have been emplaced rapidly to high level. The microdiorite shows moderate propylitic alteration. Dykes of similar rock cut the granodiorite at [6874-95895] and basement chlorite schists at [6885-95913].

The Fierro Urcu rhyolite is an irregular stock about 3×2 km in area. It is widely brecciated, enriched in disseminated pyrite and locally nodular, probably as a result of devitrification. Typical exposures [6837-95917] comprise rubbly, massive breccias with angular fragments ranging from 20-60 mm in length. Limonite vugs and fractures are common. There appear to be two clast types, an aphyric rhyolite (?) and quartz-phyric rhyolite/tuff. Sericite is widespread, giving the rock a lustrous sheen. On the north side [6832-95919], the rhyolite displays a network of intense joint-controlled massive (1-5 m width) quartz veining.

Recent drilling of the Fierro Urcu rhyolite [6831-95919] has indicated the presence of sub-economic Au and Cu grades. However, considerable potential within the district may remain. Further rhyolite bodies and zones of silicification, commonly brecciated, have been mapped away from the main Fierro Urcu intrusion. South of Quebrada Bernabé [6855-95892] a hydrothermally brecciated tuff or rhyolite is heavily mineralised with coarse disseminated pyrite and pyrite veinlets. On the track to Purdilli there is widespread silicification, with sericite and tourmaline alteration. An andesitic lithic tuff [6866-95927] is rich in silica, sericite, stilpnomelane (developed only in more Fe-rich clasts) and disseminated pyrite (WP-640). A nearby [6873-95929] rock (acid tuff) is intensely silicified and sericitized (WP-642). It contains a pyrite/tourmaline stockwork.

6.1.3 Salvias

Intrusions with hornfelsed halos and disseminated sulphide mineralisation occur in the remote area between Paccha, Zaruma, Salvias and the high páramo of Chilla and Manú. Propylitic alteration and silicification of andesitic tuffs and lavas of the Portovelo Unit is widespread.

A granodiorite in the Río Ortega catchment [6593-96011] is rich in disseminated pyrite, with a stockwork of pyrite veinlets [e.g. 6591-96010]. It shows extreme variation in grain size. Thin sections [e.g. WP-1530, ref. 6599-96013] show evidence of large, strongly zoned, plagioclase phenocrysts within a fine, granoblastic matrix. Amphibole phenocrysts, up to 15 mm display inclusion-rich margins, and are rimmed by small biotite crystals. This obvious disequilibrium of both mineral phases and textures is consistent with rapid cooling following the emplacement of partly crystallized magma at a high level. This may, in turn, have been associated with retrograde boiling and rapid fluid loss with resulting mineralisation. The granodiorite is intruded into, or intruded by, a strongly jointed plagioclase and amphibole-phyric microdiorite with moderate propylitic alteration (WP-1532; [6600-96005]). The amphiboles are replaced by chlorite, actinolite and opaque ore. The plagioclase has common chlorite inclusions, especially along microfractures.

6.1.4 Shagli

Around Shagli (“Shaglli”) indications of mineralisation occur in association with an intrusive complex of porphyritic microdiorite and granodiorite. Many joint surfaces within the intrusive facies are covered with pyrite and the surrounding host hocks are silicified and rich in disseminated sulphides. Specimen WP-234 [6806-96497] was found to contain ca. 5% disseminated pyrite, chlorite and a small amount of epidote. As in the Río Ortega, the granodiorite shows evidence of rapid high-level emplacement, WP-233A [6793-96520] shows equigranular, moderately zoned plagioclase and amphibole (with sparse clinopyroxene) with fine granophyric masses filling the interstices. There is mild alteration of amphibole to chlorite, and plagioclase to epidote. Nearby pegmatite pods, up to 2 m across, are of tourmaline (schorl) and granoblastic quartz (WP-233). White mica replaces the tourmaline. Clay alteration of the intrusion country rock is also apparent on the access road to Shagli [6789-96482], producing orange rotten rock, orange soils and landslips.

On the Shagli-Pedernales road [6805-96533], andesitic lithic lapilli-tuffs, lavas and microdiorites show strong silicification and disseminated pyrite mineralisation. Oxidation of pyrite causes sulphur staining and epidote lines vugs. In thin section, a brecciated plagioclase and amphibole-phyric andesitic intrusive rock/lava displays moderate alteration (WP-231). While the plagioclase remains relatively fresh, the amphibole has been altered to coarse chlorite and epidote. Disseminated pyrite is widespread. The zone of alteration runs about 1 km south along the road, almost as far as the contact with the granodiorite.

6.1.5 Cerro Nudillo

On this narrow edge [6680-95888], about 14 km east of Zaruma, a rhyolite intrusion is emplaced within rhyolitic tuffs and andesites of the Portovelo Unit. There is widespread silicification and abundant disseminated pyrite.

6.2 Epithermal deposits associated with rhyolites and regional fractures

The north-northeast-striking Gañarín Belt (Pratt et al., 1997) constitutes an important regional structure, extending some 70 km from Quimsacocha through Guanazán, and possibly as far south as Zaruma (Figure 5). Numerous sub-volcanic intrusions and domes occur within or marginal to the structure (Section 4.2), with attendant zones of argillic alteration and silicification. Such alteration is clearly visible in the Santa Isabel semi-desert because of the dry climate, forming white/yellow soils and landslips (Plate 11a). Proven gold mineralisation occurs in several localities, for example at Gañarín and Quimsacocha, but many additional prospects of predominantly low-sulphidation epithermal character remain essentially underexplored.

6.2.1 Interpretation

The Gañarín Belt controlled the emplacement of various rhyolite stocks and dykes, and sited volcanic centres such as the Quimsacocha and Jubones calderas (Sections 3.8.5, 4.2). Intrusions were emplaced over a considerable time span, known to range from ca. 27 Ma for the Pachagmama rhyolite (Kennerley, 1980; Appendix 1) to less than 10 Ma for the Quimsacocha rhyolite (Section 3.14). Indeed, the preservation of the Quimsacocha Caldera in such a strongly uplifted area may suggest a much younger age. Mineralisation in calderas is commonly associated with resurgent rhyodacite domes and may post-date caldera formation by millions of years (Francis et al., 1983), thus supporting a very young age for at least some of the mineralisation.

On the basis of available data, the Gañarín Belt can be tentatively interpreted as a fracture-controlled series of volcanic centres. In the case of Quimsacocha, the centre was clearly a large andesitic stratovolcano which collapsed into a caldera. The less well defined Jubones Caldera probably straddled the Gañarín Belt (Section 3.8.5), and was invaded by irregular rhyolite bodies after collapse. Other rhyolite bodies in the belt may have intruded analogous volcanic edifices, which have since been completely removed by erosion. Alternatively, they may represent isolated silicic volcanoes or domes, unrelated to calderas. The predominantly crystal-poor character of these emplacements suggests that they constitute the final, characteristically metal rich, products of magma chamber purging. The large andesite plugs present may represent sub-volcanic porphyries.

6.2.2 Gañarín Belt details

The principal prospects of the Gañarín Belt, commencing with the most northerly, are described below. Also see Section 4.2.

6.2.2.1 Quimsacocha**:** At Quimsacocha [6978-96645] (Figures 1, 5) a laterally extensive zone of epithermal mineralisation is centred on a brecciated, intensely silicified and kaolinized rhyolite body. Vugs lined by yellow acicular quartz are common. Flow banding is generally steep to vertical and parallel to the caldera margin. Planar ribs, 2-3 m wide, are widespread, reflecting stronger silicification along fractures. In thin section (WP-1568), igneous textures have not been recognized, raising the possibility that, as at Fierro Urcu, altered andesite country rocks are included with the “intrusion”. Disseminated pyrite is widespread, supergene oxidation of which has produced concentrically banded, mammilated limonite in fractures and joints. A low pH fluid regime relative to that prevailing at other Gañarín Belt prospects is indicated by localised alunitisation. Enargite and cinnabar also occur. A proven reserve of ca. 600000 ounces of Au has recently been established. A swarm of north-south striking faults, with minor displacements, cuts the east side of the caldera, in the Río Quinuahuayacu [6991-96638]. It is also cut by northeast faults.

Plate 11a. Gañarín Belt. Zone of advanced argillic alteration and silicification in the Saraguro Group. Zone is over 1 km in length. Trigopamba [6758-96290]

Plate 11b. The silica "cap" at Gañarín. Exposures in the abandoned Cuenca-Machala road [6798-96360]. Vuggy texture is clearly visible

***6.2.2.2 Hacienda Cristal and Río Falso*: ** An obvious zone of hydrothermal alteration is passed on the road to Quimsacocha. It extends about 2 km from north to south and reaches a maximum width of about 500 m. Quarries at Hacienda Cristal [6991-96554] provide good exposures of bleached clay-altered andesite lavas. The replacement has perfectly mimicked the original igneous texture, with a virtually isotropic clay mineral replacing all the minerals (WP-282). Vein networks of cream kaolin cut the rock. A higher quarry [6987-96569] comprises kaolinized and pyrite-rich bleached andesite breccias.

***6.2.2.3 Río Lluchir*:** Large areas of hydrothermal alteration are present in this river [6940-96580]. Bleached rocks and associated landslips are very visible from San Fernando. Silicification, clay-alteration, disseminated pyrite and alunite are reported.

***6.2.2.4 San Pablo*:** A small area of hydrothermal alteration [6905-96527], about 400 m by 100 m, was noted within massively bedded andesitic tuff breccias, tuffaceous sandstones and crystal tuffs in the cliffs overlooking San Fernando. It comprises silicified, clay-altered and pyritized rocks which seem to follow an east-striking fracture.

***6.2.2.5 Cañaribamba*:** The Cañaribamba prospect [6860-96437] north of Santa Isabel is associated with a rhyolite dome or stock. Donated samples from the prospect include chalcedony rock with common silicified high-spired gastropods, consistent with sinter activity. The rhyolite (BN-213) is remarkably fresh, with plagioclase, quartz and biotite crystals in a very fine-grained flow-foliated matrix. A petrographically identical rhyolite at an analogous stratigraphic level at La Paz de Portovelo [6883-96406], some 4 km to the southeast of Cañaribamba, suggests a possible sill or flow. This rock, at least 50 m thick, displays a horizontal flow-foliation and is also plagioclase-, quartz- and biotite-phyric. In contrast, it has suffered strong devitrification, with chlorite rosettes overprinting the matrix (WP-202).

***6.2.2.6 Dandán*:** The small rhyolite stock at Dandán [6810-96365] has a clay alteration zone. The matrix and plagioclases are strongly clay-altered (no sericite) (WP-191). There is also weak silicification.

***6.2.2.7 Gañarín*:** This prominent crag overlooks the Río Minas. The flat-lying stratigraphy is interpreted to comprise (in ascending order) andesitic tuffs and lavas, the Jubones Formation and a cap of silicified rhyolitic tuff breccias, overlain with angular unconformity by andesitic tuff breccias of the Santa Isabel Formation. The andesitic breccias contain large, locally flow banded, rhyolite pods up to 30 m or more in diameter, interpreted as mélange. Vertical north-northeast-striking veins (036-90) a few centimetres thick cut the silicified cap, the Jubones Formation and the underlying andesitic tuffs. These veins are currently worked for Au by artisanal miners.

The Gañarín silica cap is about 40 m thick and is well exposed on the old Cuenca-Machala road. It comprises a massive, very fine silica rock with common angular rock fragments and sparse large quartz crystals in the matrix (Plate 11b). The sequence appears to be partly sedimentary. Silicified tuffaceous sandstones and thinly bedded lithic tuffs are exposed on the crag [6797-96355] and in the drill core immediately above the Jubones Formation. Silicification does not appear to extend into the Santa Isabel Formation. This unit has been dated at about 18 Ma (Hungerbühler and Steinmann, 1996), suggesting that the mineralisation could pre-date the unconformity. The 3D geometry of the silica cap is, however, uncertain. Because of the topography it is not clear if it actually continues beneath the andesites of the Santa Isabel Formation. It is thus possible that the cap reflects a relatively recent (Pleistocene) sinter terrace, perched on the slope.

Grab and chip samples from the north-northeast trending quartz veins at Gañarín show Au values of up to 12-15 gm/ton. Channel samples of exposures of the silicified sequence in the Cuenca-Machala road varied between 1.8 and 8 gm/ton Au (pers. comm., Grantmining, December, 1996).

6.2.2.8 Pachagmama**:** The 1 km wide Pachagmama rhyolite [6750-96315] is the largest of the Gañarín Belt intrusions. It is at the heart of the proposed Jubones Caldera (Section 3.8.5), with affinities to the Quimsacocha intrusion with respect to clay-altered (kaolinization) and disseminated pyrite mineralisation. Intense weathering has produced widespread sulphur-staining of surfaces. Small adits, for example [6724-96326], are probable gold trials. A large zone of similar alteration occurs within the country rock on the eastern flank of the intrusion [6770-96323].

6.2.2.9 Trigopamba**:** A zone of alteration [6758-96290] at Trigopamba occurs on the east flank of a plagioclase and amphibole-phyric andesite stock with dimensions of 1.5 km by 2 km. Thin sections, indicate propylitic alteration of the intrusion (WP-111), and surrounding acid tuffs and andesite lavas of the Saraguro Group are intensely clay-altered (Plate 11a). Most of the rocks are powdery with sulphur- and limonite-stained weathering surfaces. All have a high concentration of disseminated pyrite. On the west flank of the Quebrada Calabozo [6757-96291] a strongly silicified breccia, similar to that at Gañarín, occurs. This appears to overlie the clay-altered (kaolin), pyritized zone. A possible rhyolite intrusion occurs in the same quebrada [6758-96287], although it is intensely clay-altered. A short distance downstream, an andesitic crystal tuff displays strong propylitic alteration. The matrix is rich in fine chlorite. Coarse epidote is clustered around the altered augites.

***6.2.2.10 Cuchicorral*:** A further zone of strong argillic alteration occurs 5 km to the southwest of Trigopamba, associated with the dyke extension of the Pachagmama rhyolite. In this area [6720-96279] the rhyolite is locally brecciated, vuggy and limonite-stained. Feldspar and quartz phenocrysts occur. The country rocks are andesites and andesitic lahars. The strongest area [6710-96275] of alteration lies on the southwest flank of the intrusion, comprising a zone of ca. 400 m × 200 m of white, kaolinized andesite. Feldspar phenocrysts are altered to a pale green mineral, probably chlorite. The argillic alteration zones at Cuchicorral are quite localized. Plagioclase- and amphibole-phyric andesite lavas, with only weak propylitic alteration, occur less than 400 m to the south of the heart of the most intense argillic alteration. The plagioclases are fresh, and the mafics have gone to calc + chl + mt + stilp (WP-789).

***6.2.2.11 Guanazán*:** This prospect was not visited, but it is interpreted as a hot spring deposit (pers. comm. Edgar Pillajo, October 1996).

***6.2.2.12 Zaruma/Portovelo*:** In the south of the mapped area, the Gañarín Belt passes the west side of the Salvias metamorphic inlier [6600-95960], a few kilometres southwest of which lies the mineralized zone of sub-volcanic rhyolite stocks of Zaruma/Portovelo described in detail in Section 6.4. This important mining district may constitute a further example of fracture-controlled volcanism, rhyolite emplacement and mineralisation potentially attributable to the Gañarín Belt. Road exposures of the Zaruma rhyolites [6534-95928 and 6537-95931] display silicified aphyric rhyolite with common sugary, recrystallized texture and vugs lined by yellow, euhedral quartz. Locally [6535-95925] the rock is brecciated and kaolinized, with abundant disseminated pyrite. In this condition, igneous textures are generally destroyed (e.g. WP-747) and the intrusive facies are thus difficult to distinguish from similarly altered andesites of the Portovelo Unit (Plate 1b).

6.3 Mesothermal, base metal- and gold-bearing veins and breccias

These deposits are typified by breccias, pods and dykes of tourmaline and silica rock. They occur in granodiorite intrusions (particularly where their cupolas are in contact with welded ash-flow tuffs), in microdiorite stocks, and in the country rocks. Possible structural controls have been noted for example, in the continuation of the Chaucha-Río Jérez Lineament, which includes Tres Chorreras, Uzhcurrumi, La Tigrera, La Playa, Gigantones and other, newly discovered, quartz/tourmaline pipes/dykes. The deposits, from north to south, are described below.

6.3.1 La Enramada

A large pipe or pod of quartz/tourmaline/muscovite rock (WP-251) about 30 m in diameter was encountered close to La Enramada [6598-96518] in the trace of the Chaucha-Río Jérez Lineament during a traverse from Quinuas to Ponce Enríquez. The pipe is located at the edge of a large sequence of lithic tuffs with metamorphic pebbles (Las Trancas Formation). There is a nearby granodiorite cupola. Sulphides were not noted.

6.3.2 Tres Chorreras

This prospect, a site of artisanal mining, comprises irregular stocks of feldspar-, amphibole- and quartz-phyric microdiorite intruded into poorly consolidated lithic tuffs and welded, pumice-rich, rhyolitic ash-flow tuffs of the Saraguro Group (the Narihuiña tuffs). The sequence was tilted eastwards to about 30-60°, and locally to vertical (on the ridge west of Quinuas), prior to the eruption and deposition of the Jubones Formation (cf. 23 Ma). The mineralised breccias are surrounded by a large halo of disseminated tourmaline extending hundreds of metres into ash-flow tuffs. Entering this halo from the north [6637-96505], about 300 m north of the first glory holy, the appearance of the tuff starts to change. Small rosettes of tourmaline appear, apparently filling vugs and holes left by leached feldspar crystals, and the rock is silicified. Larger vugs are filled with hematite and tourmaline. The pumices were important sites for tourmaline growth, presumably because they were more porous.

The Tres Chorreras mine comprises glory holes developed in the mineralised breccias, with a characteristic assemblage of massive molybdenite, hematite, chalcopyrite, pyrite and tourmaline. Banded textures are common, with several generations of tourmaline deposition and brecciation. The breccias are developed mainly within the intrusion, especially at the contacts with the dacitic tuffs. The form of the glory holes indicates that most of the breccias are vertical, elongated bodies, usually parallel to the country rock/intrusion, faulted contact. The highest glory hole [66355-965045] is developed at a microdiorite/tuff contact and displays argillic alteration. The intrusion is clay-altered, sericitized, brecciated and rich in disseminated pyrite. Fractures are filled with crustiform, banded chalcedony, euhedral clear quartz and mammilated limonite. The remaining breccias are mainly within propylitic or rarely, sericite-altered microdiorites. The intrusions do not seem to contain tourmaline. This may reflect a chemical control, a reaction, between the acid tuff and the boron-bearing fluids.

The style of mineralisation at Tres Chorreras appears to be dictated by competence. The intrusion/tuff contacts were clearly sites of increased tectonic fracturing. There is no evidence that these breccias represent hydrothermal (diatreme) breccias. There is no rounding, entraining of clasts in vertical zones or injection of matrix material into clasts.

As well as the spectacular glory hole mineralisation, veins are developed in poorly consolidated lithic tuff-breccias beneath the more compact tuffs. Crude bedding is defined by changes in clast size, as well as composition. The largest clasts are about 0.25 m in diameter. There is some indication of channelling. The tuff-breccias contain steep swarms of thin (5-10 mm) planar quartz veins, aligned north-northeast. These carry small amounts of galena, chalcopyrite, pyrite and sphalerite. Artisanal miners report gold grades of about 100 gm/ton. Visible gold is common. The presence of planar, very continuous quartz veins suggests that the rock was once more indurated and brittle than it is now. This may indicate subsequent weak propylitic alteration.

There are sheared, foliated zones within the intrusions and along the faulted contacts. They mainly strike northeast and dip steeply to shallowly northwest. They are very weathered and rich in limonite. An adit which cuts one shear zone ran 2.7 gm/ton gold over a horizontal, cross-strike distance of 10 m (pers. comm., Grantmining, December, 1996).

6.3.3 La Playa Mine [6520-96430]

This site, 12 km southwest of Tres Chorreras, was not visited because it was recently invaded by artisanal miners. It comprises 3 or 4 sub-vertical breccia pipes, in a northwest-trending line, within a granodiorite cupola. The cupola is extremely close to the contact with the La Fortuna Formation, a major angular unconformity. It is therefore possible that the mineralisation reflects some type of fluid barrier. Each pipe is roughly 100 m in diameter and comprises tourmaline (schorl) and quartz breccias with variable contents of sulphides and oxides. Samples from the site include substantial chalcopyrite, specular hematite, scheelite (?), sphalerite and bornite. Secondary minerals include azurite and malachite, but the supergene enrichment zone has long been stripped off the La Playa Pipe, the most important of the pipes. Other gangue minerals include well-formed amethyst crystals.

The La Playa breccias are variable in grain size and illustrate several generations of tourmaline growth; earlier phases are represented by angular clasts within the fine breccia, and the final phase by large radial sprays growing along joint surfaces. There is no sign, within any of the samples, of inclusions of the host granodiorite or of the ash-flow tuff (La Fortuna Tuff) which the pipes probably intrude. Gold from the site is very fine. It may be free or as inclusions within sulphides.

Grades recorded from some of the sulphide-rich portions of the pipes are 2-4 gm/ton, with ca. 40 gm/ton Ag (pers. comm., Ecuanor, April, 1996).

6.3.4 La Tigrera Mine [6512-96446]

Occurs across the watershed from La Playa, and is located in the same granodiorite intrusion. At least one quartz/tourmaline breccia is exploited, again with common sulphides and very fine gold. There is less tourmaline than at La Playa. The breccia pipe is thought to be vertical and lies virtually at the contact between the cupola and the La Fortuna Formation.

6.3.5 Uzhcurrumi

Vein deposits have been worked formerly around Uzhcurrumi and there are several indications of polymetallic and gold mineralisation. Visible gold, in irregular veins with green copper minerals and possible cinnabar, was found at Lacay [6588-96329], in a newly opened road, during the present survey. It occurs in clay-altered dacitic tuffs close to a large granodiorite intrusion, which is apparently offset by a northeast fault. Intense silicification is evident in Saraguro acid tuffs 2 km to the west [6570-96331]. Around the north fringe of the same granodiorite intrusion propylitic alteration of both the intrusive facies and the country rocks is observed. There are also veins that have been worked by levels. At [6592-96343] joint zones and narrow veins a few centimetres thick are mineralised with chalcopyrite, epidote, pyrite, tourmaline, galena and molybdenite. The main structures strike 032° and dip 82° west. A loose block of solid galena, 0.1 m in diameter, is apparently derived from the hillside above the levels. Nearby levels [6613-96343] are driven on veined fault gouges with quartz, pyrite and galena.

6.3.6 Others

Other examples of quartz/tourmaline/sericite pods, pipes and dykes have been located and deserve follow-up work. They are listed on the 1:50000 sheet:

a) Uzhcurrumi: A foot traverse downstream of Tres Chorreras encountered [9636-96476] a tourmalinized tuff with coarse sericite/muscovite (WP-244) within the Saraguro Group.

b) Uzhcurrumi: Thin quartz/tourmaline veins occur in quartz/feldspar crystal-rich ash-flow tuff (Saraguro Group) west of San Rafael [6589-96366].

c) Paccha: A breccia pipe of tourmaline, quartz, sericite, epidote and abundant arsenopyrite occurs at Río Cristal [6488-96045] near Paccha. The brecciated rock fragments are a fine granodiorite. The outcrop is about 150 m by 70 m. The 3D geometry is not known. A wide halo of tourmaline occurs in the country rocks. A much smaller pipe crops out nearby [6493-96043]. The pipes occur within a granodiorite intrusion and alongside a hornfelsed microdiorite intrusion (also tourmaline-bearing). The age relations between the two intrusion types are not proven, but the hornfelsing suggests that the microdiorite is the older, perhaps an earlier intrusive phase of the granodiorite. A tourmaline-rich granodiorite also crops out near the antennas [6464-96074], north of Paccha.

d) Selva Alegre: A dyke-like zone of hydrothermal alteration occurs within a porphyritic andesite/microdiorite sill (?) on a crest [6736-95988] southeast of Taurococha. The “dyke” strikes north and continues for at least 1 km. The width is approximately 100 m. The zone comprises limonite-stained, silicified intrusive rock with vugs and joints lined by euhedral quartz and tourmaline. The intrusive rock has a sugary, silicified texture. No sulphides were seen. In thin section, the rock displays a granoblastic quartzose mosaic with coarse tourmaline sprays (WP-1631). Original mafic phenocrysts are completely chloritized. The matrix is rich in sericite and chlorite. The host intrusion has a wide extent and displays mild (regional or local?) propylitic alteration.

6.4 Combined epithermal and mesothermal, base metal-poor, gold-bearing veins

6.4.1 Zaruma-Portovelo

This historically important mining zone (Andrade, 1911; Baragwanath, 1912; Billingsley, 1926; UNDP, 1969b) comprises swarms of gold-bearing veins within rhyolite stocks and andesites of the Portovelo Unit. The veins are mainly north-south-striking. The mineralisation seems to drop off rapidly to the west of the Río Galera [6517-95910] in the outcrop of the less indurated, andesitic and dacitic tuffs of the Saraguro Group.

Two vein types have been recognized by the Misión Belga (1989a, b) within the Zaruma-Portovelo field. Polymetallic (auriferous) mesothermal veins contain quartz and a wide range of sulphides (pyrite, chalcopyrite, sphalerite, galena, bornite, chalcocite, covellite and oxidised equivalents, malachite, hematite and limonite), with refractory Au contained within the pyrite and chalcopyrite. Free Au is also present. Fluid inclusion studies indicate deposition temperatures of 320-380°C for these veins (Shepherd *In* Litherland, 1987), which are best exemplified in the Portovelo-Zaruma-Malvas belt. Epithermal quartz-calcite veins are sulphide-poor and richer in precious metals, with Au typically free. Sparse sulphides include pyrite, chalcopyrite, galena, sphalerite. Sulphosalts include proustite (Ag sulphosalts). Adularia in the wallrocks, and absence of alunite, imply an adularia-sericite type epithermal model (Heald et al., 1987). Fluid inclusion studies by the Misión Belga suggest that the precious metals precipitated between 200-300° by boiling. An NaCl equivalent to 2.5-7.4% weight percent is present in the inclusions. A strong influence from meteoric waters is implied. The calculated depth of mineralisation in the epithermal veins is 300-600 m.

The most recent mineralisation model for Zaruma/Portovelo (Misión Belga, 1989a, b; Van Thournout et al., 1991) defines a circular (caldera) structure some 9-10 km in diameter, to which the zone of propylitic alteration of the Portovelo Unit andesites is considered to be confined. The contrasting mineralisation assemblages present are interpreted within the model as reflecting pre-caldera mesothermal and post-caldera epithermal systems, and the rhyolite intrusions are correlated with Chinchillo (now Saraguro Group) volcanism. From information collated during the present study, the validity of this model may be questionable. Propylitic alteration has for example, been found to constitute a regional characteristic of Portovelo Unit. No topographic evidence of a caldera-type structure has been noted, and displacement of lithological boundaries at the supposed caldera margin has nowhere been observed. While the numerous rhyolite stocks are consistent with the presence of a volcanic centre (possibly a caldera), the current evidence is not sufficient to define its location or size. Such a centre may, therefore, plausibly be interpreted as the southernmost expression of the Gañarín Belt (Section 6.2).

6.4.2 Bella Rica and Tres Ranchos

Gold-bearing quartz veins at Bella Rica and Tres Ranchos (Figure 9), south of the Gaby porphyry (Section 6.1), are emplaced within basalts of the Pallatanga Unit. Typical exposures [6448-96588] comprise green basalts, dolerite and hyaloclastites with an irregular stockwork of epidote, quartz and chlorite veins up to 20 mm thick. Alteration spots of epidote are common and reach 50 mm in diameter. Similar zones of epidote surround some veins. The rock has an apparent magnetic susceptibility of 25.4 emu (Appendix 4).

Disseminated pyrite and pyrite stockworks are widespread at Bella Rica. Although primary clinopyroxene generally remains intact, thin sections from Bella Rica display variable propylitic alteration (WP-1664, 1666, 1667). Actinolite and albite are widespread within veinlets in the propylitized wallrocks of a northeast vein at [6445-96598] (WP-448). Actinolite also replaces hornblende phenocrysts. Towards the Gaby porphyry, on the Bella Rica access road [6436-96613], vugs filled by tourmaline, epidote and sulphides appear (WP-1668).

The area is bounded by a series of major west-northwest-striking faults (Figure 9). In the south, a fault follows the Río Margarita; in the north, a fault follows the Río Tenguel. A third major fault, the serpentinite-filled Río Chico Fault, occurs in the San Gerardo (Pinglio) to Tenguelillo areas. Within this block, most veins and faults, including the major Tres de Mayo Fault, strike north or north-northwest. The bulk of mineralized veins dip 45-65° towards the east. There are also three important transverse, broadly east-striking faults: Guanache, Los Ratones and Pueblo Nuevo.

The most important mineralisation in the Bella Rica concession is a system of north-northwest trending veins about 3 km long, with a known width of 400 m (Misión Belga, 1996). Individual veins have variable dip and strike and can change quite abruptly. There are between 6 and 12 principal veins, mainly less than 0.6 m, rarely up to 1 m. Pinch and swell is common. The main minerals in order of importance are pyrite, pyrrhotite, arsenopyrite, sphalerite, galena and hematite. Visible gold is rare. Supergene alteration products include chalcocite, covellite, cuprite, malachite, goethite, lepidocrocite and limonite. Gangue minerals are mainly quartz with minor calcite, ankerite, ferro-dolomite, chlorite, muscovite and epidote.

6.4.3 San Gerardo (Pinglio) to Tenguelillo

This zone is probably an extension of the Bella Rica district. The stratigraphy of the area is complex. The lower flanks of the hilly area are formed of basalts, while the highest parts comprise welded dacitic tuffs and deeply weathered andesitic tuffs (probably representing an outlier of the Saraguro Group). Most of the vein deposits occur within the former. As at Bella Rica, the zone is constrained between two east-southeast faults: the Río Tenguel Fault and the east-southeast-striking, serpentinite-filled Río Chico Fault. Little is known about the style of gold mineralisation, other than that it is of vein type. There is a variety of vein and fault orientations, but the bulk are northeast-southwest, some are north-striking and a few are parallel to the Río Chico Fault. The occurrence along the northeast faults of serpentinite films indicates that at least some were active during movements on the Río Chico Fault. They can thus be considered a complementary set to the latter.

Green, sheared rocks along a northeast fault near San Gerardo [6541-96630] display serpentinite-coated surfaces. A thin section shows a fine-grained intrusive rock, probably dolerite rich in clinopyroxene (WP-152). It shows propylitic alteration, with epidote and calcite veinlets and much chlorite/calcite replacement of the matrix. A level [6522-96651] displays silicified green andesite or microdiorite with numerous irregular shear zones and slickensided faults. The tunnel is driven on a mineralized fault (173/66 W).

A large body of serpentinite occurs within Bella Rica Basalts at Tenguelillo [6605-96600]. It is elongated northeast and has a northeast foliation and is probably another example of a serpentinite-filled northeast complementary fracture. A window of metamorphic rocks, interpreted as sheared Pallatanga Unit basalts, crops out to the west (Section 3.1). To the east, a large granodiorite intrusion probably links with the Chaucha batholith. The granodiorite and surrounding basalts are widely hornfelsed (cordierite + muscovite), for example at [6614-96602] (WP-1657). There is widespread disseminated pyrite in the country rocks, for example at [6617-96584], and the granodiorite. The position of the Tenguelillo serpentinite body, within Bella Rica Basalts and at the southeastern limit of the Río Chico Fault, a structure that may have been instrumental in mineralisation, suggests that this area is worth further investigation.

6.4.4 Modelling the Bella Rica/San Gerardo mineralisation

It is tempting to include the serpentinite-filled faults in any modelling of the vein mineralisation. Their general steep attitude implies strike-slip (vertical intermediate compressive stress, σ_2). There are two theoretical strike-slip models (Figure 9): a) simple conjugate faulting, b) Riedel shear. The first requires the horizontal maximum compressive stress (σ_1) to bisect the acute angle between the fault sets (Figure 9). It would hence be aligned at about 080°. In the second model, the Río Chico Fault might be interpreted as an R_1 (synthetic) shear and the complementary faults as R_2 (antithetic) shears (Figure 9). Both models could mean only sinistral movement on the Río Chico and parallel faults (Río Tenguel, Río Margarita). However, the north-south veins at Bella Rica imply east-west extension and a major problem with strike-slip models is that they are not strongly dilational. This suggests the mineralisation is not associated with serpentinite emplacement and strike-slip. More likely, faults that developed in a strike-slip regime suffered later east-west extension.

The association of gold mineralisation with the Bella Rica Basalts, at both Bella Rica and San Gerardo, may reflect the greater abundance of background gold in basic rocks compared with acid rocks (Tilling et al., 1973). If the basalts provided the source of the gold, then large-scale circulation of meteoric/submarine waters would be required. It is easier to imagine this in a submarine setting than in a terrestrial volcanic arc.

6.5 Volcanogenic massive sulphides (VMS)

A possible VMS type occurrence has been seen northwest of San Fernando [6886-96558]. It occurs in the Turupamba Formation, and may be an epithermal-related deposit of the Gañarín Belt. Road exposures show distorted, slumped pyritous fine acid tuffs with sparse coal fragments. There are also pyritous conglomerates with an unusual form; all clasts are of fine tuff and the matrix is virtually indistinguishable. We interpret them as intraformational. Veins of kaolin also occur.

The United Nations Development Programme (UNDP, 1969a) drilled sulphide-rich mineralisation northeast [6961-96585] of San Fernando, in andesites and andesitic debrites of the Quimsacocha and Turi Formations. It is interpreted as exhalative (Goossens, 1972). The UNDP deposit has not been visited, but it lies a short distance from Quimsacocha and we suspect that it may be related to the belt of epithermal mineralisation of the Gañarín Belt.

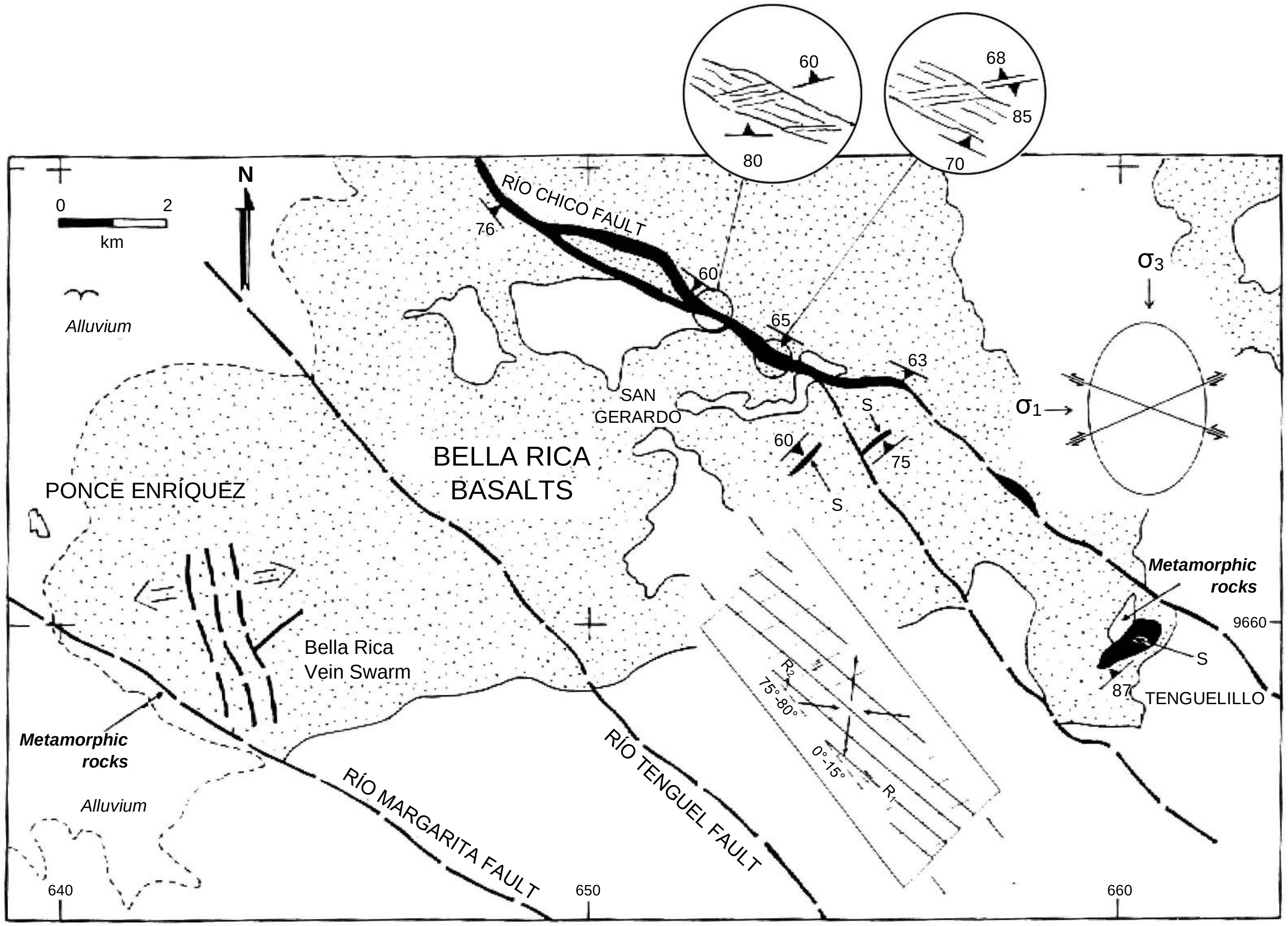

Figure 9. Tectonic models for the faulting around Ponce Enríquez. Serpentinite in black. Blank areas are post-Bella Rica strata and intrusions. Insets show details of the foliated serpentinites. Two possible models for the serpentinite-filled Río Chico Fault and complementary northeast faults are show: a) conjugate strike-slip, b) Riedel shear (Tchalenko, 1970; Tchalenko and Ambraseys, 1970). See text for explanation

6.6 Travertine

Travertine, a source of ornamental stone and of lime for cement, is found along the major faults and thrusts of the district. Uraninite has been reported by some (UNDP, 1971). La Cría [6837-96232], the largest deposit, is being worked for cement. Like Baños (near Cuenca) (DGGM, 1980c), it comprises a narrow, steep-sided ridge with an axial fracture through which hot springs emerged. La Cría is developed on a major, northwest-verging thrust within the Girón Fault System (Section 5). This structure marks the eastern limit of the Ayancay intermontane basin. A very small deposit of travertine [6814-96239] occurs on another thrust, marking the western limit of the Ayancay basin. Within the basin, the well-known 'Mina de Mármol' [6836-96230] worked material was deposited along the steeply-dipping, faulted contact between the Jubones Tuff and the Ayancay Group, on the west flank of the La Cría Anticline. Veins are mainly concordant. The travertines of Saraguro [6971-96018] were not visited, but appear to lie on a north-striking fault.

The travertines represent recently expired, or still-active, hydrothermal systems. Remnant magmatic heat drove, and is still driving, circulating meteoric water. The carbonate is probably leached from the andesites (Santa Isabel Andesites, Sacapalca Andesites) in the volcanic pile. Calcite-veined andesites crop out in the vicinity of most of the travertine deposits. The faults that fringe the former Santa Isabel sedimentary basin were clearly important fluid pathways.

6.7 Building stone

The best building stone is probably the intrusive dacite south of Saraguro. It is a non-jointed freestone that is easily sawn. A small quarry [6941-95954] provides paving stone for the streets of Saraguro. The potential resource is enormous.

7. GEOPHYSICS

Analysis of the total magnetic field for southern Ecuador (Figueroa, 1995), corrected for the near equatorial latitude, produces a good correlation with the major structures. Figure 10 is a map of the total magnetic field with the digitised geological map overlain. In this way, it is possible to appreciate how well the regional structures, such as the Gañarín and Girón fault systems, correspond with magnetic discontinuities. The map shows a distinct east-west grain, perhaps reflecting the grain of the metamorphic basement. In general, areas of metamorphic rocks show lower gradients and higher values than volcanic rocks. The wide spacing between isolines shows that, not surprisingly, the metamorphic rocks are deeply rooted. The páramo south of Manú and Chilla is marked by a similar response: high magnetism and low gradients. This implies that the Saraguro Group/Celica Andesites must be thin, an observation supported by the occurrence of metamorphic windows in the area. A similar anomaly is present at the junction of the Ríos Naranjo and León, suggesting that metamorphic rocks may be present at shallow depth beneath the Sacapalca Andesites. In contrast to the páramo of Manú, the páramo of Pedernales, Quinuas and San Fernando, north of Santa Isabel, gives a large negative anomaly, probably reflecting a great thickness of volcanic rock.

Crossing the east-west grain, the Gañarín Belt cuts various saddles. In the south of the area, the profound contrast in magnetic properties between the metamorphic and volcanic rocks (Celica Andesites) is obvious, although the strongest gradients occur a few kilometres north of the Piñas-Portovelo Fault System. This supports our model of a gently north-dipping thrust, with metamorphic rocks in the footwall (Section 5).

Unfortunately, insufficient magnetic susceptibility readings (Appendix 4) are available to model the data set in detail. However, it is clear that the volcanic rocks, which are mainly flat-lying, have very variable magnetism. That is partly why most sharp gradients occur in the volcanic outcrop. Depending on the derivative used in future assessments, it will be important to consider the effects of these shallow sources.

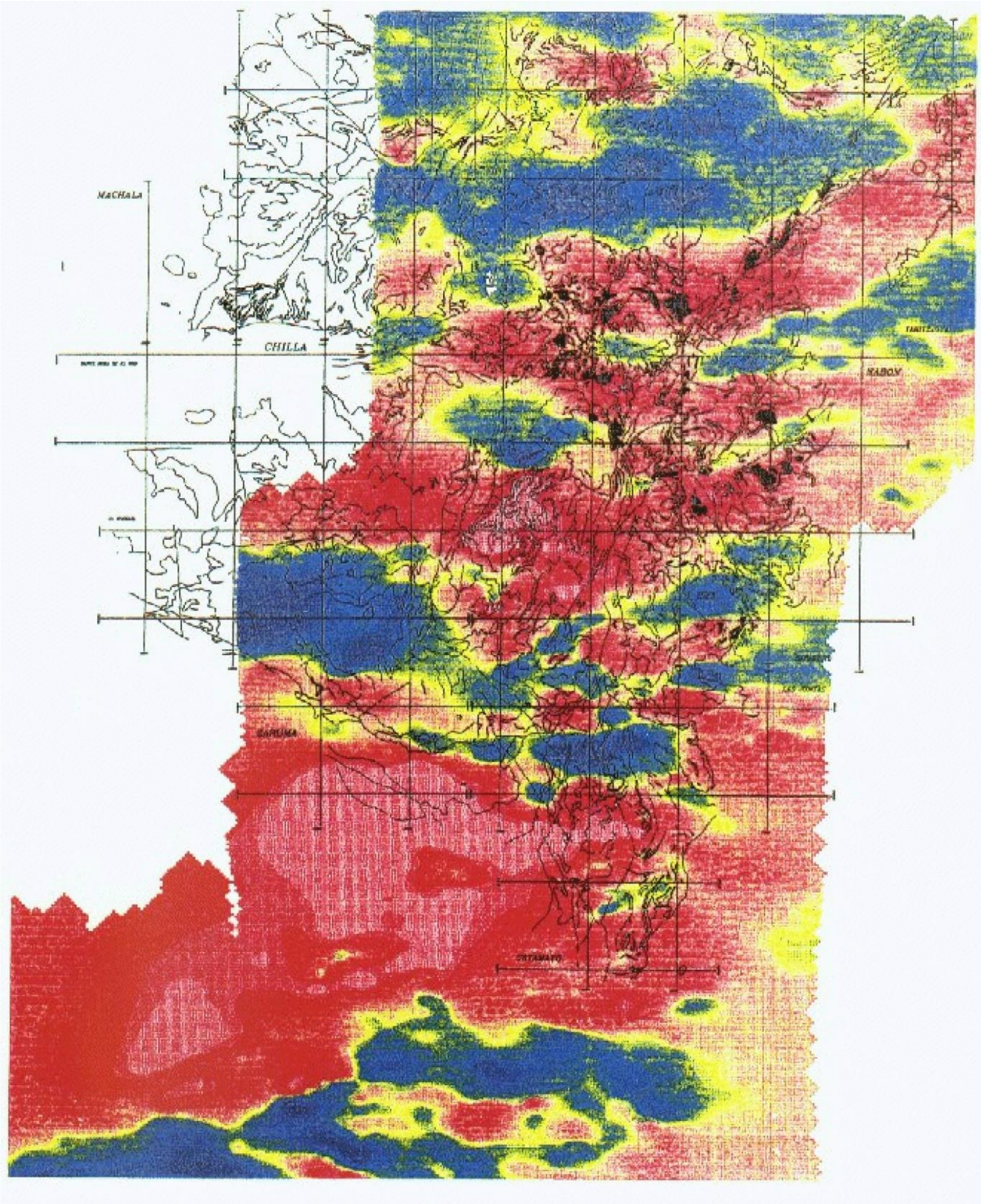

Figure 10. Map of the total magnetic field grid with the digitised geological map overlain upon it. Pink corresponds with positive (high) values, blue with negative (low) values

8. GEOLOGICAL HISTORY

The oldest rocks of the mapped area, present to the south of the Piñas-Portovelo Fault, belong to the metamorphic basement of the Cordillera Real-El Oro structural block, metamorphosed during a regional event in the Late Triassic. The diverse, predominantly metasedimentary, rocks of the El Oro metamorphic complex (Aspden et al., 1995) are interpreted as part of an accretionary prism complex, that includes the above high-grade rocks of Triassic age, most probably from a Paleozoic protolith, lower grade rocks of probable Jurassic-Cretaceous age that comprise the matrix of the prism/mélange and high-pressure rocks of Early Cretaceous age tectonically emplaced into the mélange. North of the Jubones Fault, the majority of the metamorphic rocks present belong to the lower-grade Jurassic-Cretaceous units of the accretionary prism complex, the probable western limit of which is the Bulubulu Fault (Dunkley and Gaibor, in press) that separates it from the oceanic rocks of the Pallatanga Unit to the northwest.

The Bella Rica Basalts of the Pallatanga Unit interpreted as oceanic (MORB) crust, are considered to be part of an ophiolite sequence that was accreted to the South American continental margin in the Late Cretaceous most probably in the Campanian. The calc-alkaline volcanics of the poorly defined Celica Unit, were deposited in a terrestrial to marine ensialic arc and are perhaps, at least in part, contemporaneous with the Bella Rica Basalts. The cessation of activity in the Celica arc in the Campanian (Feininger and Bristow, 1980) may reflect the above accretion of the Pallatanga (Piñón) terrane. The overlying Maestrichtian Yunguilla Unit is a turbidite sequence derived from the erosion of arc material (?Celica) and the metamorphic rocks of the Cordillera Real-El Oro block following uplift as a result of the accretion of the oceanic rocks of the Pallatanga terrane.

The Quingeo Formation and the (?)contemporaneous and younger continental volcanic arc rocks of the Sacapalca Unit and Saraguro Group accumulated in a trough between the Western Cordillera and the uplifted Cordillera Real. The Sacapalca Unit andesites may be the southern equivalents of the Macuchi islands arc basalts. Syn-depositional faults, developed above major basement faults, such as the Gañarín Belt and Girón Fault System, constrained basins, volcanic centres and high-level intrusions. During the Oligocene and Miocene, the focus of deformation appears to have moved eastward, with tilting first at Narihuiña, Pedernales, San Pablo de Cebadas and Chaucha, at about 24-26 Ma. A major rhyolitic ash-flow tuff province developed in the latest Oligocene and earliest Miocene time, followed shortly after (19-16 Ma) by a phase of granitoid emplacement. A major caldera developed southwest of Santa Isabel and was the source of at least one major ash-flow tuff (Jubones Formation). At about 18 Ma, accelerated east-west extension resulted in intermontane basin sedimentation at Santa Isabel, Girón, Cuenca and Catamayo. This may reflect a change in the direction of plate convergence between the mainland and the Nazca Plate or because of rollback of the subduction zone. At about 10 Ma a major compressive event, dated by the truncation of deformed Ayancay Group by the Uchucay Formation, inverted the basins and thrust Saraguro and Sacapalca strata over the intermontane basins.

The Turi and Tarqui Formations are probably at least in part contemporaneous. The former represents an outwash from an andesitic volcano (?Quimsacocha). The Tarqui Formation was deposited in an environment that varied between deltaic, lacustrine and fluvial and it is possible that Quimsacocha may have been a source for some of the acid ash-flow tuffs of this formation.

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BRITISH GEOLOGICAL SURVEY and CORPORACIÓN DE DESARROLLO E INVESTIGACIÓN GEOLÓGICO MINERO Y METALÚRGICO (In press-b) Geological map of the Western Cordillera, Ecuador between 2 and 3 degrees south. (1:200000). (BGS, Nottingham; CODIGEM, Quito).

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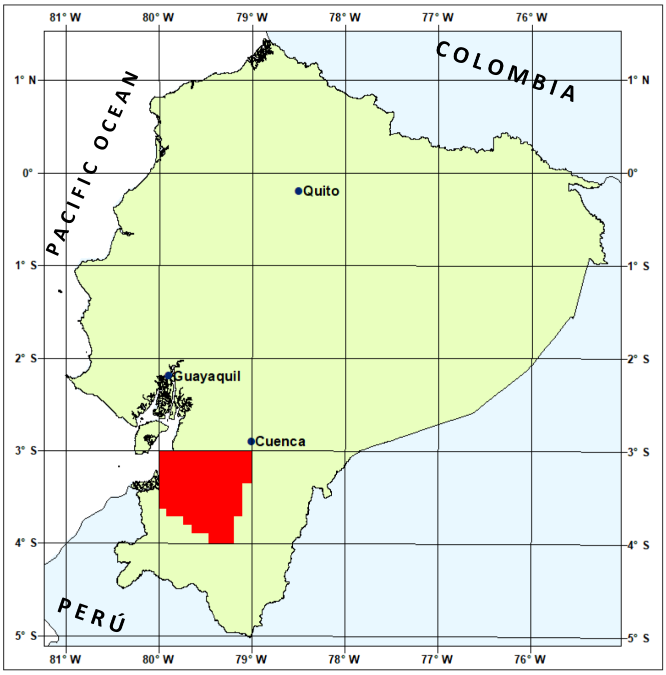
APPENDIX 1 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 3°00’ AND 4°00’ S

RADIOMETRIC AGES



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 1 AREA)

QUITO, 1997

Table 1. New radiometric ages

SAMPLE (WP)	UTMX	UTMY	SHEET	ROCK TYPE	AGE (Ma)	METHOD
10	6763	96363	Santa Isabel	Jubones Tuff Formation	22.76 ± 0.97	K/Ar (biotite)
14	6635	96347	Uzhcurrumi	Granodiorite	19.92 ± 0.18	K/Ar (hornblende + biotite)
176	6324	96354	Machala	La Fortuna Tuff Formation	23.2 ± 0.8	f/t
233	6793	96518	San Fernando	Granodiorite	17.64 ± 0.61	K/Ar (biotite)
275	6619	96509	Ponce Enríquez	Saraguro Group	27.7 ± 1.0	f/t
298	6907	96293	Manú	Saraguro Group	26.7 ± 1.1	f/t
472	7038	96192	Nabón	Saraguro Group	25.0 ± 0.9	f/t
481	7029	96141	Nabón	La Paz Tuff Formation	22.5 ± 0.9	f/t
509	6902	96297	Manú	Saraguro Group	22.4 ± 1.0	f/t
620	6817	96203	Manú	Sacapalca Formation	24.8 ± 1.8	f/t
623	6792	96144	Manú	Gneiss	36.5 ± 3.5*	f/t
653	6941	95954	Selva Alegre	Dacite intrusion	9.6 ± 0.5	f/t
717	6727	96144	Manú	Saraguro Group	20.7 ± 2.4	f/t
765	6502	95916	Zaruma	Saraguro Group	21.5 ± 0.8	f/t
1600	6471	96060	Paccha	Granodiorite	16.89 ± 0.16	K/Ar (biotite)

* Range in single zircon grain ages between 130 Ma and 31 Ma

f/t = Zircon fission track, K/Ar = Potassium/Argon

Table 2. New and existing radiometric ages

SAMPLE	UTMX	UTMY	SHEET	ROCK TYPE	AGE (Ma)	METHOD
DH-385	646051	9555116	Catacocha	Sacapalca Formation	66.9 ± 5.8	f/t
DH-394	674378	9539250	Gonzanamá	Gonzanamá Formation	14.4 ± 1.8	f/t
DH-439	674378	9539250	Gonzanamá	Gonzanamá Formation	15.7 ± 2.0	f/t
DH-443	675103	9540573	Gonzanamá	Gonzanamá Formation	14.0 ± 3.0	f/t
**DH-486	697035	9625187	Nabón	Jubones Tuff	23.0 ± 2.2	f/t
**DH-487	69703	962430	Nabón	Saraguro Group	23.4 ± 2.0	f/t
***	6729	96326	Santa Isabel	Rhyolite	26.8 ± 0.7	K/Ar (whole rock)
***	6733	96325	Santa Isabel	Andesite dykes	19.5 ± 0.4	K/Ar (whole rock)
**CH-62	68830	962940	Manú	Santa Isabel Formation	18.4 ± 2.0	f/t
**CH-66	680200	9630300	Manú	Jubones Tuff Formation	26.0 ± ?	f/t
**MS-237	681310	9630790	Manú	Jubones Tuff Formation	20.0 ± ?	f/t
**MS-238	683500	9634000	Santa Isabel	Ayancay Group	14.7 ± 0.6	f/t
**MS-239	683296	963398	Santa Isabel	Santa Isabel Formation	18.4 ± 1.6	f/t
***	698200	9643100	Yaritzagua	Santa Isabel Formation	14.2 ± 0.5	K/Ar (whole rock)

** dates from the Swiss research group (Hungerbühler and Steinmann, 1996; Hungerbühler, in prep.)

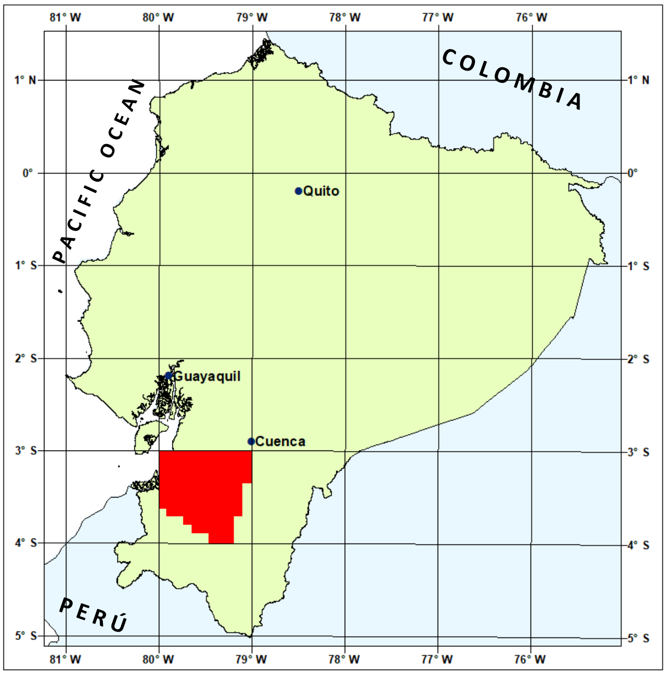
*** from Kennerley (1980)

f/t = Zircon fission track, K/Ar = Potassium/Argon

APPENDIX 2 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 3°00’ AND 4°00’ S

GEOCHEMICAL DATA



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 1 AREA)

QUITO, 1997

Table 1. Whole rock geochemistry

Rock type	Tuff	Granodiorite	Granodiorite	Rhyolitic tuff	Quartz diorite	Tuff	Andesitic tuff	Lithic Tuff	Hyaloclastite	Dacitic tuff
Sheet	Santa Isabel	Uzhcurrumi	Uzhcurrumi	Machala	San Fernando	Ponce Enríquez	Yaritzagua	Manú	Ponce Enríquez	Manú
UTMX	6763	6635	6541	6324	6793	6619	6982	6907	6448	5902
UTMY	96363	96347	96327	96354	96518	96509	96431	96293	96586	96297
Unit/Gp./Fm.	Jubones			Saraguro		Saraguro	Santa Isabel	Saraguro	Bella Rica	Saraguro
Sample	**WP-10**	**WP-14**	**WP-21B**	**WP-176**	**WP-233**	**WP-275**	**WP-278**	**WP-298**	**WP-452A**	**WP-509**
SiO_2	77.25	59.23	53.67	77.77	55.16	71.53	61.87	66.49	46.71	68.19
TiO_2	0.22	0.81	0.84	0.10	0.88	0.33	0.53	0.58	0.75	0.32
Al_2O_3	12.21	16.92	16.64	12.77	17.84	14.07	17.12	15.77	11.88	14.13
Fe_2O_3	1.88	7.57	9.51	0.98	8.49	3.15	5.38	4.92	11.33	3.76
MnO	0.03	0.14	0.15	0.02	0.16	0.07	0.12	0.10	0.23	0.25
MgO	0.30	3.47	4.71	0.07	4.59	0.76	2.64	0.81	9.11	0.54
CaO	1.53	6.62	8.14	0.46	8.08	2.06	5.87	2.70	11.43	3.15
Na_2O	2.50	2.54	2.03	2.21	2.31	3.13	2.60	2.28	1.64	1.88
K_2O	3.20	1.67	0.54	4.27	1.09	3.00	0.77	4.66	0.22	3.13
P_2O_5	0.06	0.17	0.12	0.02	0.20	0.06	0.13	0.13	0.07	0.06
LOI	0.73	0.38	3.11	0.83	0.93	1.62	2.97	1.21	6.80	4.48
Total	**99.91**	**99.52**	**99.46**	**99.50**	**99.73**	**99.78**	**100.00**	**99.65**	**100.17**	**99.89**
Ba	782	587	189	1462	377	1192	376	792	45	946
Ce	39	33	15	46	15	19	8	27	11	38
Co	0	23	34	0	31	8	13	11	32	0
Cr	5	28	74	4	66	7	58	10	167	0
Cs	1	1	2	1	2	0	1	0	1	5
Hf	5	0	5	0	5	9	7	0	9	0
La	16	12	6	32	7	24	12	16	5	22
Nb	8	6	5	9	5	10	4	6	5	9
Nd	20	20	8	29	15	16	10	19	5	22
Ni	5	22	25	5	24	6	6	11	57	5
Rb	120	67	19	178	30	119	16	169	4	127
Sc	1	21	36	4	26	10	18	15	43	14
Sm	3	0	0	6	12	0	12	7	2	8
Sr	145	339	184	62	469	184	470	202	79	411
Ta	0	0	0	0	0	0	0	0	0	0
Th	8	1	2	14	2	8	1	4	1	5
U	4	2	1	2	0	4	0	2	2	4
V	25	169	248	0	213	39	92	88	295	26
Y	20	27	23	23	16	24	10	19	21	25
Zr	89	134	87	99	110	182	94	180	42	198

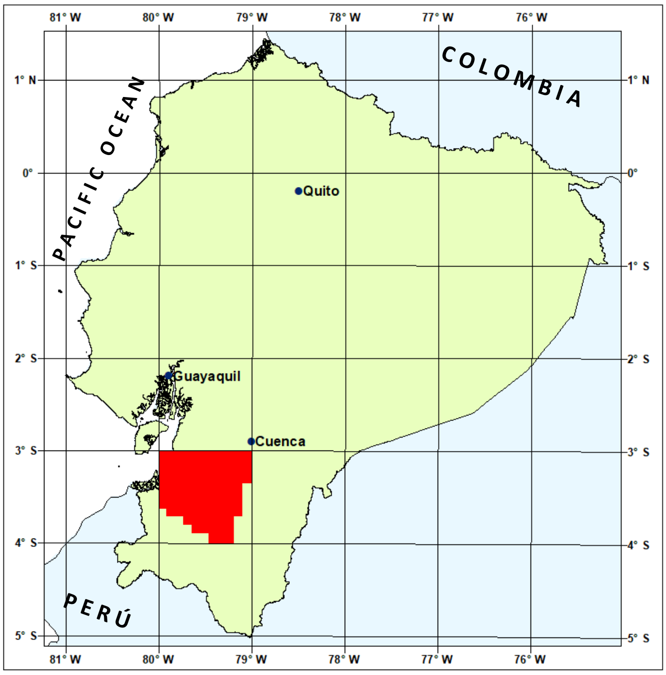
Table 2. Whole rock geochemistry (*continuation*)

Rock type	**Andesite**	**Dacite**	**Dacite**	**Dacitic tuff**	**Andesite/dacite**	**Andesitic tuff**	**Tonalite**	**Gabbro/diorite**	**Gabbro/diorite**	**Basalt**	**Gabbro/dolerite**
Sheet	Manú	Selva Alegre	Manú	Zaruma	Selva Alegre	Zaruma	Paccha	Ponce Enríquez	Ponce Enríquez	Ponce Enríquez	Ponce Enríquez
UTMX	6817	6941	6727	6502	6693	6623	6471	6435	6434	6436	6486
UTMY	96203	95954	96144	95916	95948	95895	96060	96611	96612	96613	96676
Unit/Gp./Fm.	Sacapalca		Saraguro	Saraguro	Portovelo	Portovelo				Bella Rica	
Sample	**WP-620**	**WP-653**	**WP-717**	**WP-765**	**WP-1525**	**WP-1548**	**WP-1600**	**WP-1666**	**WP-1667**	**WP-1668**	**WP-1670**
SiO_2	58.27	69.09	68.15	63.63	57.50	57.16	61.57	50.12	50.41	51.08	51.49
TiO_2	0.93	0.41	0.54	0.48	0.87	0.76	0.63	0.86	0.94	1.13	1.03
Al_2O_3	16.59	17.65	15.54	16.45	18.77	16.68	17.26	13.86	14.29	14.03	14.93
Fe_2O_3	7.85	2.10	4.50	4.58	7.13	7.47	6.80	11.12	12.21	12.60	11.48
MnO	0.13	0.02	0.09	0.10	0.13	0.11	0.11	0.20	0.20	0.19	0.16
MgO	3.62	0.00	1.05	1.89	3.46	4.86	2.88	8.24	7.98	7.37	6.09
CaO	6.35	3.68	3.70	3.68	7.54	6.43	6.29	10.33	9.57	9.19	10.32
Na_2O	2.25	4.13	3.39	3.96	2.21	1.41	2.64	2.62	2.26	1.89	2.33
K_2O	1.37	1.69	2.14	1.97	0.63	1.45	1.01	0.13	0.15	0.12	0.17
P_2O_5	0.18	0.16	0.14	0.11	0.16	0.11	0.13	0.07	0.08	0.09	0.07
LOI	2.27	0.60	0.83	2.75	1.82	3.16	0.55	2.23	2.00	1.71	1.34
Total	**99.81**	**99.53**	**100.07**	**99.60**	**100.22**	**99.60**	**99.87**	**99.78**	**100.09**	**99.40**	**99.41**
Ba	597	903	703	535	320	434	319	52	0	17	18
Ce	25	12	36	29	34	19	26	11	23	28	0
Co	23	0	8	15	12	28	9	47	48	36	46
Cr	39	7	7	18	63	122	20	191	186	119	20
Cs	0	2	1	0	0	1	1	1	1	0	1
Hf	0	4	4	0	8	0	8	7	5	7	0
La	16	16	24	11	14	9	8	0	9	0	4
Nb	6	5	8	5	9	6	4	5	6	5	5
Nd	17	17	23	12	22	15	15	7	8	11	8
Ni	21	0	7	10	11	25	12	109	87	65	53
Rb	48	43	71	55	26	51	40	1	0	3	2
Sc	24	9	13	9	25	25	18	39	51	50	44
Sm	13	8	11	15	7	6	26	0	11	0	0
Sr	300	681	240	274	308	263	328	127	116	85	120
Ta	0	0	0	0	2	3	0	0	0	4	0
Th	1	3	2	4	3	2	2	1	1	1	1
U	3	0	2	0	0	0	0	0	2	0	0
V	170	55	55	82	147	161	148	295	329	376	349
Y	23	4	28	12	28	16	23	18	23	25	23
Zr	144	119	186	98	134	119	122	48	56	69	57

APPENDIX 3 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 3°00’ AND 4°00’ S

PETROGRAPHY



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 1 AREA)

QUITO, 1997

Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-8B	Ponce Enríquez	6587	96515	Dacitic crystal tuff	Common angular qtz. crystals	Intense epidotization	Saraguro
WP-10	Santa Isabel	6763	96363	Crystal-rich tuff	Common feld/qtz/bt crystals	Devitrification	Jubones
WP-14	Uzhcurrumi	6635	96347	Fresh rock. Quartz diorite	Bt/horn/plag and qtz		Intrusive
WP-21B	Uzhcurrumi	6541	96327	Granodiorite	Mainly amph, some bt. Bt replaces amph.	Weak mica alteration of feld.	Intrusive
WP-22	Uzhcurrumi	6570	96330	Difficult rock. Tuff or rhyolite?		Intense hydrothermal. Seric, epid, silica, chlor.	Saraguro
WP-26	Uzhcurrumi	6492	96329	Basalt. Fractured	Plg and cpx-phyric	Epidote, calcite, white mica. Not strong. Regional type.	Bella Rica
WP-36	Uzhcurrumi	6588	96329	Acid tuff	Common qtz. and plag.	Strong hydroth. White mica/clay. Recrystallized matrix.	Saraguro
WP-51B	Uzhcurrumi	6657	96349	Dacitic Crystal tuff	Crystal-rich. Little matrix	All mafic crystals to chlor + white mica. Plag rich in epid inclusions.	Saraguro
WP-52	Santa Isabel	6719	96323	Rhyolite	Euhedral and embayed qtz.	Plag phenos clay-altered. Matrix recrystallized.	Intrusive
WP-53D	Uzhcurrumi	6643	96834	Crystal-rich tuff. Andesitic to dacitic		Strong hydroth. Plag to seric, epid. Mafic to epid, chlor. Silicif.	Saraguro
WP-82	Uzhcurrumi	6632	96318	Clast. Andesite lava		Plag recrystall. also contains calcite. Mafics to chlor/epid.	Santa Isabel
WP-87	Santa Isabel	6669	96316	Andesite	Plag + horn-phyric	Fairly fresh. Mafics to stilpnomelane.	Santa Isabel
WP-89	Manú	6677	96293	Andesite		Fairly fresh. Similar to WP87.	Santa Isabel
WP-111	Manú	6748	96310	Andesite		Fairly fresh. Horn to magnetite, chl, stilp?	Intrusive
WP-113	Manú	6798	96306	Crystal-rich tuff	Qtz, plag, bt.	Fresh. Radiating globe devitrific. Some bt to chl.	Jubones
WP-118	Uzhcurrumi	6466	96344	Fine granodiorite	Plag-phyric. Plags not zoned	Mild. Plag with inclusions + calc. Mafics to mt, calc, stilp, chl.	Intrusive
WP-140	Santa Isabel	6748	96319	Dacite/rhyolite Flow-foliated	Plag-phyric. Plags not zoned	Fresh	Intrusive
WP-143	Manú	6677	96269	Andesite	Plag + amph-phyric. Sheared. Calc veins	Strong Plag-cal + mica. Amph-mt/opaq + mica. Matrix to calc + qtz.	Santa Isabel
WP-152	Ponce Enríquez	6541	96630	Microdolerite	Equigranular plag + CPX. Interstitial glass? to chlorite	Mod fresh. Epid + calc veins. Calcite in matrix. Serp on joints.	Bella Rica
WP-153	Ponce Enríquez	6497	96651	Diorite/gabbro	Amph + plag	Mild. Plag inclusion rich. Chl + epid + calc. Amph rich in exsolved opaq ore.	Intrusive
WP-158A	Uzhcurrumi	6425	96338	Dolerite	Primary horn + plag	Mild. Interstit glass to chl?. Sparse epid. Vugs of calc + chl + qtz.	Bella Rica
WP-162	Uzhcurrumi	6538	96488	Andesitic crystal tuff		Fresh	Fortuna
WP-169	Santa Isabel	6747	96426	Andesite. Flow-foliated. Devitrified	Plag + amph-phyric	Mod. Plag to calc + qtz + chlor. Amph to opaques + chlor. Thin calc veins.	Saraguro
WP-172	Santa Isabel	6727	96410	Rhyolitic breccia-pyroclastic	Shards visible	Strong silicification. May be devitrification.	Saraguro
WP-172A	Santa Isabel	6727	96410	Rhyolite	Qtz phenocrysts	Completely devitrified with globe form.	Saraguro
WP-176	Machala	6324	96354	Matrix-rich rhyolitic tuff	Ab. embayed quartz. Small bts.	Fresh.	Fortuna
WP-178	Uzhcurrumi	6397	96330	Micaceous calcareous sandstone (sst) with foraminifera	Mica, Qtz, fossils	Weak.	Bella Rica
WP-189	Santa Isabel	6797	96355	Rhyolitic Crystal tuff (prob. welded)	Bt, qtz, plag	Strong. Plag to clay/mica. Bt to chl, opaq. Qtz veins. Radiating devitrify.	Jubones
WP-191	Santa Isabel	6816	96375	Rhyolite flow-foliated. Microlites	Phenos feld + sparse qtz	Hydroth. Strong. Clay/white mica alteration especially of plag phenos.	Intrusive
WP-196	Manú	6758	96287	Andesitic crystal-rich tuff.	cpx	Hydroth, mod CPX to amph, chl, epid, mt, calc. Felds rich in epid, calc.	Saraguro
WP-198	Santa Isabel	6705	96334	Crystal-tuff	Plag + qtz + bt	Devitrified. Hydroth? Plag to calc. Some plag to clay. Bt to chl, calc, mt.	Jubones
WP-202	Santa Isabel	6883	96406	Rhyolite. Flow foliated.	Plag + sparse qtz/bt phenos.	Rosette star devitrification	Saraguro
WP-204	Santa Isabel	6788	96366	Perlitic fracture rhyolite glass. Aphyric		Radiating globe, chlorite devitrification	Intrusive?
WP-208	Santa Isabel	6767	96378	Rhyolite glass. Flow foliated. Aphyric		Fresh version of 204, slight devitrification	Intrusive?
WP-209	Santa Isabel	6746	96416	Flow foliated and lava	Phenos plag + amph? + sparse bt	Mod. Plag to calc + clay/white mica. Matrix fresher. Mafics to epid. calc.	Saraguro

Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-211	Santa Isabel	6750	96433	Glassy. Flow foliated and lava	Plag, cpx, horn phenocrysts	Fresh	Saraguro
WP-217	Santa Isabel	6726	96441	Glassy. Flow foliated rhyolite. Perlitic fracture		Devitrification + chlorite replacement	Saraguro
WP-221	Santa Isabel	6867	96407	Andesite/dacite lava	Bt, plag, amph phenocrysts	Weak. Bt is Fe-enriched	Saraguro
WP-226	Santa Isabel	6833	96395	Andesite lava, intrusive	Plag + amph phyric	Fresh	Intrusive
WP-231	San Fernando	6805	96533	Andesite lava or intrusive	Feld + amph phyric	Moderate. Plag still fresh. Amph to chlor + epid. Much opaq (pyrite?)	Saraguro
WP-233	San Fernando	6793	96520	Pegmatite	Qtz, tourmaline, musc. Coarse	Fresh. Tourmaline locally to musc.	Intrusive
WP-233A	San Fernando	6793	96520	Granodiorite, granophyric matrix	Cpx + amph	Mild. Amph to chlorite, small amount of epidote	Intrusive
WP-234	Santa Isabel	6806	96497	Intrusive?		Strongly silicified. Pyrite + chlor + epidote	Intrusive?
WP-235	Santa Isabel	6687	96447	Andesite lava. Flow foliation	Plag + mafic phenocrysts	Weak. Mafics to amph. Matrix rich in chlorite and opaque ore	Intrusive?
WP-237	Santa Isabel	6689	96427	Andesite lava/intrusive	Plag and cpx-phyric	Strong. Chl, epid, opaq ore widespread in matrix. Mafic to amph + epid	Santa Isabel
WP-244	Uzhcurrumi	6636	96476	Tuff or sst.	Qtz + feld + rock fragments (metamorphic)	Strong. Hydrothermal. Clay alt of felds + tourmaline	Saraguro
WP-248	Ponce Enríquez	6591	96509	Lithic tuff with lava	Metamorphic clasts (qtz + musc)	Strong. Propylitic. Rich in epidote + chlorite	Saraguro
WP-251	Ponce Enríquez	6598	96518		Qtz, musc, tourmaline	Fresh. Rock has several generations of tourm growth + muscovite	Hydrothermal
WP-252	Ponce Enríquez	6588	96514	Conglomerate	Clasts of psammite + feathery feld/amph bas	Mild.	Trancas
WP-273	Ponce Enríquez	6442	96600	Basalt lava		Veins of epid, qtz, chl, opaq ore + calcite. Matrix to amphibole + sphene	Bella Rica
WP-274	Ponce Enríquez	6590	96563	Andesite crystal tuff	Common andesite lithics	Radiating chlorite devitrification. Mafics to chlorite	Saraguro
WP-275	Ponce Enríquez	6628	96514	Eutaxitic dacitic tuff. Fe-enriched matrix		Mild.	Saraguro
WP-275A	Ponce Enríquez	6628	96514	Eutaxitic dacitic tuff	Plag + qtz + mafic crystals	Radiating chlorite devitrification. Mafics to chlorite	Saraguro
WP-278	Yaritzagua	6982	96431	Andesitic crystal tuff	Plag + amph + bt	Mild. Mafic to stilp, chl. Plag crystals have inclusion. Bts Fe-enriched	Santa Isabel
WP-280	San Fernando	6938	96519	Acid tuff		Strongly silicif and recrystall. Plags to qtz. Broken qtz crystals survive	Saraguro
WP-282	Girón	6991	96554	Andesite	Amph + plag-phyric	Intense. Perfect clay replacement	Turi
WP-289	Yaritzagua	6999	96421	Acid tuff or rhyolite	Scattered qtz, bt + altered feld crystals	Devitrified	Saraguro
WP-295	Yaritzagua	6983	96375	Eutaxitic acid tuff	Vitroclasts	Mild. Inclusion-rich plag phenocrysts	Saraguro
WP-296	Yaritzagua	6969	96369	Eutaxitic andesitic or dacitic tuff	Plag + sparse amph phenocrysts	Very fresh. Devitrified matrix	Saraguro
WP-298	Manú	6907	96293	Eutaxitic tuff	Plag crystals. Sparse pumices	Fresh. Some devitrification	Saraguro
WP-298A	Manú	6907	96293	Eutaxitic acid tuff	Plag + spars amph crystals	Mild. Plag fresh	Saraguro
WP-304	San Fernando	6862	96553	Andesite	Plag + amph-phyric. Matrix visibly igneous as 308	Fresh	Intrusive
WP-306	San Fernando	6865	96557	Lithic crystal tuff	Pumice	Fe-enriched. Plag to clay	Turupamba
WP-307	San Fernando	6886	96558	Tuffaceous siltstone. Burrows?		Disseminated pyrite. Felds to white mica or clay	Turupamba
WP-308	San Fernando	6884	96560	Andesite as 304	Plag + amph phyric	Moderate. Plag to clays. Amph to chlor	Intrusive
WP-311	Manú	6825	96217	Andesite	Plag + amph phyric	Moderate propylit. Mafics to epid, chl. Plag to epid, chl. Similar to Zaruma rocks	Sacapalca
WP-314	Girón	6181	96599	Coarse eutaxitic dacitic tuff	Plag + qtz + bt crystals	Mild. Felds to clay	Sacapalca
WP-322	Yaritzagua	7147	96387	Basalt or intrusive. Flow foliated		Fresh olivines? to stilp + chlor	Saraguro
WP-323	Yaritzagua	7198	96473	Andesite similar to 375	Plag + amph + bt-phyric	Weak	Intrusive
WP-326	Santa Isabel	6909	96476	Andesite	Plag + cpx phenocrysts. Cpx has finer cpx rims	Fresh	Intrusive
WP-328	Santa Isabel	6909	96462	Dacitic pumice tuff	Large andesite fragments	Mild	Saraguro
WP-332	Santa Isabel	6884	96467	Basalt/andesite	Plag + cpx phyric	Mild. Mafics to chlor + calcite. Matrix devitrified	Saraguro
WP-338	Girón	7208	96537	Lava/intrusive. Dacite?	V. f grain. Plag, bt, qtz-phyric	Devitrification. Plags are inclusion-rich	Saraguro

Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-346	Girón	7220	96578	Sandstone	Metamorphic + igneous clasts	Fresh	Yunguilla
WP-352A	Girón	7028	96643	Andesite flow-foliation	Plag + cpx phyric	Fresh	Quimsacocha
WP-375	Girón	6978	96657	Quimsacocha. Lava/intrusive. Flow foliated as 323	Plag, amph, bt-phyric	Fresh	Intrusive?
WP-377	Girón	6985	96633	Quimsacocha Rhyolite?		Strong. Silicified, Fe-oxides	Intrusive
WP-383	Girón	7203	96575	Dacite lava.	Plag phyric. Flow foliated glassy matrix	Fresh. Inclusions in plag	Tarqui
WP-394	Santa Isabel	6892	96415	Rhyolite. Flow foliated	Plag + qtz (embayed) + large bt phenos	Mild	Intrusive
WP-405	San Fernando	6797	96589	Crystal-rich tuff as 113	Qtz, plag, bt crystals	Mild. Devitrified. Plag to calcite	Jubones
WP-425	San Fernando	6792	96619	Acid tuff	Pumice fiamme in exposure	Devitrified. Plag + matrix to calcite. Mafics to calcite + chlor	Turupamba
WP-429	San Fernando	6722	96618	Granodiorite/tonalite	Plag, amph. Large zoned plag megacrysts	Mild. Plag to epidote (minor). Mafics to chlor + calcite	Intrusive
WP-430	San Fernando	6719	96623	Rhyolite?		Mod. Epid veins. Fe oxides in veins. Clay/white mica, chl alt is comm.	Intrusive
WP-439	San Fernando	6698	96658	Gneiss	Bt + qtz + chlor + amph	Mild. Plag to clay + white mica. Amph to mica + sphene?	Metamorphic
WP-442	San Fernando	6685	96646	Variolitic basalt	Cpx + plag. Magnet? rods. Prob glass patches	Minor. Veins of chl	Saraguro
WP-446	Ponce Enríquez	6631	96663	Tonalite	Plag (strong zoned), qtz, bt	Fresh	Intrusive
WP-448	Ponce Enríquez	6445	96598	Variolitic, aphyric basalt	Plag + mafic	Strong. Mafic to act. Veins of act, epid, opaq, plag, qtz. Epid only in veins	Bella Rica
WP-452A	Ponce Enríquez	6448	96586	Hyaloclastite glassy		Strong. Calcite + actinol + chl + sphene	Bella Rica
WP-453	Chilla	6613	96158	Porphyritic microdiorite.	V. f. matrix. Amph phenocrysts (after cpx?)	Strong. Plag-epid. Amph-chl. Plag is inclusion-rich. Small amount of qtz	Intrusive
WP-454	Chilla	6632	96158	Porphyritic andesite/microdiorite	Plag, amph phenocrysts. Chl fills vugs	Strong. Mafic to chl, calc. Plag to mica. Hydroth? No epid. Matrix v. alt.	Intrusive?
WP-456	Manú	6682	96158	As 457. Eutaxitic crystal tuff	Plag + bt + cpx + amph	Fresh. Bt-stilp. Devitrified and recrystallized	Saraguro
WP-457	Manú	6686	96152	As 456. Eutaxitic crystal tuff	Plag + bt + sparse qtz + cpx	Fresh. Matrix is Fe-enriched. Bt-stilp	Saraguro
WP-458	Manú	6689	96152	Flow-foliated rhyolite. Fe-enriched matrix	Plag + qtz crystals	Fairly fresh. Globe recrystallization/devitrification	Intrusive
WP-483	Saraguro	7022	96123	Microdiorite	Plag + amph phyric	Slide too poor to see	Intrusive
WP-486	Saraguro	6989	96111	Intrusive. Very poor slide	Feld-phyric	Granoblastic texture visible. Probably silicified	Intrusive
WP-488	Saraguro	6999	96109	Acid tuff	Qtz crystals	Strong. Silicified. Recrystallized. Felds leached out. Open microfractures	Saraguro
WP-494	Saraguro	7025	96061	Rhyolite. Superb flow foliation. Aphyric		Fresh. Devitrification with chl rosettes	Tarqui?
WP-502	Saraguro	6979	96041	Andesite lava	Sparse large plag phenocrysts	Fairly fresh. Cpx to amph	Saraguro
WP-506	Saraguro	7009	96018	Andesite. Superb flow foliation	Plag + cpx. Sparse qtz crystals	Very fresh	Saraguro
WP-509	Yaritzagua	6994	96375	Vitroclastic tuff. Non-welded. Bubbles.	Common pumice	Fresh. Glass to chlorite	Saraguro
WP-509A	Manú	6902	96297	Vitroclastic tuff pumice	Coarse shards. Scatter lithics	Fresh. Glass to chlorite	Saraguro
WP-510	Saraguro	6987	96003	Basaltic andesite. Flow foliated. Very similar to 511	Plag, cpx-phyric	Glassy, fresh	Saraguro
WP-511	Saraguro	6975	96006	Similar to 510. Basaltic andesite. Flow-foliated	Plag, sparse cpx	Fresh, glassy	Saraguro
WP-513	Saraguro	6946	96075	Rhyolite or ignimbrite		Strong. Silicified, recrystallized (granoblastic) much white mica (?) growth	Saraguro
WP-533	Selva Alegre	6915	96120	Microdiorite	Large plag. Matrix is plag, bt, calcite, mt, chl	Weak. Mafics to chl. Stilp veinlets	Intrusive
WP-556	Selva Alegre	6904	96061	Ignimbrite	Vague vitroclasts. Common qtz crystals	Strong. Silicification. Much opaque ore	Saraguro
WP-573	Selva Alegre	6898	96120	Andesite. Flow foliation	Common large plag phenos	Mod. granoblastic devitrifi. Plag phenos have clays. Amph to stilp (?)	Intrusive
WP-583	Selva Alegre	6842	96141	Andesite crystal tuff	Ab: amphibole. Common zircons	Strong. Plag to clay minerals. Matrix to chlorite	Saraguro
WP-595	Selva Alegre	6822	96085	Sandstone	Lava clasts, plag crystals, sparse qtz. Lack of mafics	Mild. Chlorite in matrix	Yunguilla
WP-597	Selva Alegre	6819	96078	Basaltic andesite/andesite. Flow-foliated	Plag + sparse cpx phenocrysts	Abundant biotite/stilpnomelane disseminated in matrix and all phenos	Yunguilla
WP-605	Selva Alegre	6806	96106	Andesitic crystal tuff or lava	Plag + mafic phenocrysts	Strong. Propyli. Mafic to chl, opaq, calc. Plag to chl, clays. Matrix to chl	Saraguro

Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-606	Selva Alegre	6807	96112	Coarse sandstone	Ab strained qtz, Ab muscovite	Moderate. Plags to clay minerals	Yunguilla
WP-609	Selva Alegre	6791	96095	Andesite lava Flow-foliated	Plag-phyric	Strong sericite and calcite	Saraguro
WP-612	Selva Alegre	6788	96102	Microdiorite	Plag + amph + cpx	Mild. Plag to clay/sericite, much calcite	Intrusive
WP-619	Manú	6814	96227	Ignimbrite	Rich in plag + qtz + bt crystals	Cataclastic deformation. Matrix to chlorite sliding along biotites	Jubones
WP-620A	Manú	6817	96203	Andesite. Good igneous texture	Plag + cpx phyric	Plag to epid + chl + calcite. Cpx to amph + chl + calcite + epid. Matrix chl	Sacapalca
WP-623	Manú	6792	96145	Gneiss	Plag, qtz, bt, musc, garnet	Mild. Plag to calcite	Metamorphic
WP-626	Girón	7087	96525	Flow-foliated rhyolite		Fresh	Intrusive
WP-627	Manú	6825	96243	Crystal tuff	Plag + qtz, some large shards	Devitrified with chl rosettes. Cataclasis (mild) with clay-filled fractures	Jubones
WP-636	Santiago	6844	95918	Fierro Urcu. Foliated rhyolite/tuff?	Qtz phyric. Broken qtz crystals	Intense silicification. Feldspars altered to clay and leached out	Intrusive?
WP-638	Santiago	6853	95919	Andesite	Plag + sparse amph phyric	Moderate. Amph locally to chl + epidote + pyrite	Intrusive
WP-640	Santiago	6866	95927	Andesitic lithic tuff. Similar to 741	Entirely clasts of lava	Strong. Much sericite, stilpnomelane, silicification and opaque ore	Sacapalca
WP-642	Santiago	6873	95929	Altered rock		Intense. Silicification, sericite, tourm in planar fractures. Disseminated pyrite (very fine)	Sacapalca
WP-648	Santiago	6896	95944	Diorite	Plag + amph	Mild. Amphs to chlorite. Sphene	Intrusive
WP-653	Selva Alegre	6941	95954	Dacite	Plag phyric. Plags strongly zoned	Mild.	Intrusive
WP-657	Santiago	6892	95917	Glomeroporphyritic andesite lava	Plag + mafic phenos	Mod. Mafic to stilp, opaq. Plags + matrix rich in white mica/clay, stilp	Intrusive?
WP-660	Santiago	6861	95892	Fine granodiorite. Equigranular. Variab grain	Amph, plag, qtz, opaq	Slight. Amph to chl. Moderately hornfelsed	Intrusive
WP-663	Santiago	6849	95888	Andesite	Feld + amph-phyric	Strong. Propyl. Plag to sericite, epid, chl. Maf to chl. Vugs calc, epid, qtz, chl	Sacapalca
WP-665	Santiago	6844	95889	Andesite. Excellent flow foliation	Plag + amph phyric	Mild. Some mafics to chl + mt	Sacapalca
WP-668	Selva Alegre	6869	96045	Andesite. Flow-foliated	Plag phyric. Amphs	Moderate. Plag has stilp inclusions. Amphs to stilp + opaque ore	Intrusive
WP-669	Selva Alegre	6846	96037	Andesite	Plag + amph-phyric	Mild. Some epid + chl + stilp inclusions in plags. Amphs to calcite + mt	Saraguro
WP-679	Manú	6770	96242	Flow-foliated rhyolite	Elongate bt + plag + qtz phenocrysts	Mild	Intrusive
WP-689	Selva Alegre	6706	96036	Poor quality slide. Andesite lava	Plag + amph phyric	Mild. Amph to chl. Plag to white mica	Saraguro
WP-692	Selva Alegre	6698	96026	Andesite	Plag + amph phyric	Strong. Plag to calc + epid + chl. Mafics to chl + calc	Portovelo
WP-710	Manú	6825	96154	Poor quality slide. Andesite. Flow-foliated	Plag + amph phyric	Moderate. Amphs to chl. Plag to chl + calc. Matrix to chl	Saraguro
WP-716	Manú	6828	96180	Vitroclastic dacitic tuff	Plag crystals	Mild. Devitrification. Qtz + chl alt. of matrix. Plag to clay (weak)	Saraguro
WP-717	Manú	6727	96144	Andesite. Flow-foliated	Plag phyric. Sparse cpx. Glassy	Mild. Devitrified. Mafics to stilp + chl. Zeolite + calcite veins	Saraguro
WP-720	Selva Alegre	6683	96129	Dacitic tuff	Rich in plag + amph + qtz crystals	Devitrifi (chl rosettes). Plag, amph to green chl where cut by fractures	Saraguro
WP-725	Paccha	6644	96103	Rhyolite	Qtz + plag + bt phenocrysts	Moderate. Snowflake devitrification. Silicification of plag	Saraguro
WP-733	Santiago	6936	95832	Andesite lava. Flow-foliated		Moderate. Plag to calc, epid. Mafics to epi, chl, calc. Matrix to calc, chl	Sacapalca
WP-736	Santiago	6938	95810	Rhyolite. Aphyric	Plag + qtz + bt	Moderate. Calcite + clay/white mica	Intrusive
WP-738	Santiago	6837	95917	Rhyolite of Fierro Urcu. Brecciated	Qtz phenocrysts	Intense. Silicific. Euhedral qtz, stilp, epid in fractures. Much limonite	Intrusive
WP-739	Santiago	6823	95915	Rhyolite/ignimbrite. Fierro Urcu	Qtz-phyric	Intense. Silicified. Plag to white mica/clay and opaque ore	Intrusive?
WP-740	Santiago	6844	95902	Silicified ignimbrite/rhyolite. Fierro Urcu	Qtz phenocrysts	Intense. Silica and sericite. Granoblastic	Intrusive?
WP-741	Santiago	6837	95898	Andesite lithic tuff	Similar to 640	Moderate. Abund diss pyrite. Chl, epid. Weak silicification	Sacapalca

Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-745	Catamayo	6839	95747	Andesite lava/lithic tuff	Vesicles of act + chl + epid	Moderate. Propyl. Matrix rich in act. Plag alt to act + calc + epid	Sacapalca
WP-747	Zaruma	6528	95929	Rhyolite?		Intense. Silicified to a micro-mosaic of quartz	Intrusive
WP-751	Zaruma	6498	95904	Poor quality slide. Acid tuff		Not determinable	Saraguro
WP-752	Zaruma	6493	95911	Difficult rock		Appears silicif. Very fine grain. Calc veins. Sheared. Limonite stains	Saraguro
WP-756	Paccha	6397	95968	Calc-schist	Fine qtz + calc + musc + epid	Mild	Metamorphic
WP-758	Selva Alegre	6677	96004	Andesite lava. Flow-foliated	Fresh cpx + plag phenocrysts	Mild. Snowflake devitrific. Mafic to chl, calc. Plag to chl, calc	Portovelo
WP-763	Paccha	6635	95985	Andesite lava	Mafic + plag phyric. Strong plag zoning	Mod. Propyl. Mafics to chl, epid. Plag to epid, chl	Portovelo
WP-765	Zaruma	6502	95916	Dacitic crystal tuff	Plag, amph, embayed qtz. Few rhyolite lithics	Mild. Calcite veins. Some mafics to chl. Plag to calc	Saraguro
WP-774	Chaucha	6861	96709	Rhyolite flow-foliated	Sparse plag phenocrysts	Devitrified. Plag to qtz + moderate. Sericite/clay	Saraguro
WP-779	San Fernando	6833	96614	Rhyolite flow-foliation	Feld phenocrysts (sparse)	Mild. Matrix fresh. Feld to calc + sparse chl	Saraguro
WP-782	Manú	6699	96306	Rhyolite. Strong flow-foliated	Plag phenocrysts + amphs, zircons	Strong devitrification (radial chl rosettes) silicification of matrix, plag, amph	Intrusive
WP-789	Manú	6713	96272	Andesite	Plag phyric. Sparse amphs, common small bt	Mild. Plag fresh. Mafic to calc, chl, mt, stilp. Matrix locally rich in stilp	Saraguro
WP-794	Santiago	6814	95872	Lava or fine intrusive	Plag-phyric	Strong hornfels. Much diss py, white mica, bt, qtz. Ign texture destroyed	Portovelo
WP-798	Santiago	6807	95838	Andesitic (?) lithic tuff		Strong. Ab calc. Mafic + plag to calc + chl. Ab diss py. Press sol seams.	Portovelo
WP-824	Catamayo	6842	95602	Similar to 841. Andesite. Flow-foliated	Feld + cpx phyric. Ab opaq	Mild. Ign texture preserved. Cpx to chl, calc. Plag to chl. No epid	Sacapalca
WP-841	Catamayo	6864	95613	Andesite. Similar to 824. Flow-foliated	Plag, mafic-phyric. Opaq ore	Mild. Mafic to chl + calc. Matrix to fine calc + chl. No epid	Sacapalca
WP-850	Catamayo	6859	95613	Andesite lava. Flow-foliated	Plag + sparse amph phenocrysts	Mild. Mafic to chl + calc. Matrix to calc + chl. No epid	Sacapalca
WP-851	Catamayo	6868	95638	Andesite lava. Flow-foliated	Plag phyric. Ab opaque ore	Mild. Chl + calc + stilp	Sacapalca
WP-859	Catamayo	6889	95693	Andesite lava	Plag + cpx phyric	Mild. Cpx to chl + calc. Matrix to chl + calc. No epid	Sacapalca
WP-866	Catamayo	6853	95724	Andesite lava or fine intrusive	Amph and plag phenocrysts	Mild. Mafics fresh. Plag has small epid + chl inclusions. Matrix to chl	Sacapalca
WP-869	Santiago	6913	95812	Andesite lava	Plag + mafic phyric. Holocrystalline	Moderate. Mafics to chl. Matrix rich in chl + calc. Plag to calc	Sacapalca
WP-881	Catamayo	6849	95703	Andesite. Flow-foliated	Glass matrix. Plag mafic phenocrysts	Mild. Mafics to chl + calc + mag + sphene. Matrix to calc + chl	Sacapalca
WP-883	Catamayo	6789	95624	Rhyolite	Plag + bt phyric	Mild. Matrix includes calc. Bt to stilp	Intrusive
WP-887	Catamayo	6751	95704	Acid tuff. Vitroclast texture in hand specimen	Broken plag + qtz	Moderate clay mineral	Sacapalca
WP-893	Catamayo	6744	95737	Basaltic andesite	Plag + cpx phyric. Glassy with microlites	Mild. Cpx to chl. Narrow zones of granoblast qtz silicific. Qtz strained	Sacapalca
WP-900	Catamayo	6776	95680	Granite?	Phenocrysts of feld + qtz	Strong. Hornfelsed matrix with qtz + feld + zoisite	Intrusive
WP-905	Catamayo	6821	95745	Andesitic lava/fine intrusive. Variable grain	Plags. Act in matrix	Mild. Epid, qtz, py veins. Actino as alt product? No epid in matrix	Intrusive
WP-924	La Avanzada	6308	96038	Schist	Qtz + cordierite + musc	Cordierite to sericite	Metamorphic
WP-944	Paccha	6409	96031	Andesite. Flow foliated	Plag + mafic phenocrysts	Moderate. Mafics to chl + calc + sphene. Plag to calc	Portovelo
WP-945	Paccha	6413	96033	Andesite lava/fine intrusive	Plag + mafic phenocrysts	Moderate. Mafics to chl + epid. Plag to coarse epid + calc	Portovelo
WP-956	Paccha	6488	96025	Very poor slide. Intrusive?	Mainly qtz + chl + epid veins	Moderate. Chl	Intrusive
WP-957	Paccha	6481	96032	Microdiorite	Plag-phyric	Moderate. Chl + act + epidote. Pervasive	Intrusive
WP-975	Chilla	6423	96143	Andesite. Flow-foliated	Mafic + plag phenocrysts	Moderate. Plag to epid. Mafic to act, epid, opaq. Veins calc, anthoph?	Saraguro
WP-1047	Santa Isabel	6686	96317	Obsidian. Rhyolite	Sparse amph + felds phenocrysts	None. Perlitic fracturing	Intrusive
WP-1125	Paccha	6584	96069	Rhyolite? or tuff	Plag + mafic phyric + sparse qtz	Moderate. Silicific. Plag to chl epid, clay (?). Mafics to py + chl + epid	Portovelo
WP-1129	Paccha	6582	96054	Acid tuff/rhyolite?	Sparse qtz crystals	Intense. Silicification + sericite + tourmaline + epid	Portovelo

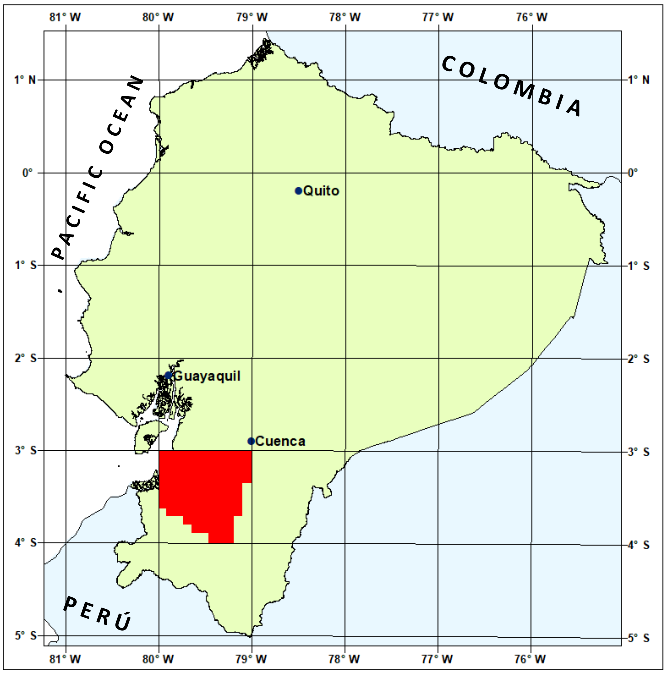
Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-1205	Ponce Enríquez	6634	96501	Welded tuff. Tres Chorreras		Moderate. Calc, chl. Plag to calc. Maf to chl, py. Clots of qtz, chl, py, tourm, act	Saraguro
WP-1210	Ponce Enríquez	6621	96503	Welded tuff	Ab feld + qtz crystals	Mild. Clay/sericite	Saraguro
WP-1216	Ponce Enríquez	6592	96503	Andesite. Crystal tuff	Ab plag, horn, sparse qtz. As 162 and 1225	Mild. Hornblende to chl	Saraguro
WP-1222	Ponce Enríquez	6554	96501	Welded tuff. As 176	Sparse qtz + plag + bt	Mild. Devitrification. Plag to clay mins	Fortuna
WP-1225	Ponce Enríquez	6545	96513	Andesite. Crystal tuff. As 162 and 1216	Ab plag, horn, sparse qtz	Mild. Hornblende to chl + stilp	Saraguro
WP-1233	Ponce Enríquez	6530	96548	Difficult rock. Tuff?	Qtz grains	If tuff, strong act + bt + chl. If intrus, mild	Trancas
WP-1234	Ponce Enríquez	6528	96552	Dacitic crystal tuff. Similar to 1233	Some metamorphic clasts	Moderate. Much fibrous act + chl	Trancas
WP-1237	Ponce Enríquez	6519	96562	Silty mudstone/siltstone	Few large muscs	Mild. Chl + stilp	Trancas
WP-1502	Santiago	6817	95873	Welded rhyolitic tuff	Ab embayed qtz + plag	Moderate. Plag + matrix to coarse sericite. Also clay?	Sacapalca
WP-1504	Santiago	6808	95828	Andesitic lithic tuff	Ab pumices	Moderate. Propyl. Pumice + maf to chl. Plag to calc, chl. Matrix to calc, chl	Sacapalca
WP-1505	Santiago	6807	95826	Rhyolite. Glassy. Flow foliated	Plag phyric	Moderate. Hornfels. Granoblast qtz patches. Plag to clay. Opaq ore	Intrusive
WP-1508	Santiago	6774	95796	Difficult. Strongly foliated hornfels rock. Very fine grain	Spots	Strong hornfels	Portovelo
WP-1513	Santiago	6744	95886	Sandstone	Coarse quartz. Common musc + sparse bt. Zircons	Fresh	Saraguro
WP-1520	Santiago	6703	95884	Dacite/andesite. Very similar to 1125	Plag-phyric	Mild. Matrix recrystallized-appears silicified. Ab pyrite	Saraguro
WP-1521	Santiago	6696	95884	Andesitic crystal tuff	Amph + plag and lithics. Sparse qtz crystals	Moderate. Amph to chl. Plag to coarse epid. Tourm sprays	Portovelo
WP-1523	Santiago	6683	95885	Rhyolite. Aphyric flow-foliated		Mild. Hornfelsed. Some tourm	Intrusive
WP-1524	Santiago	6681	95887	Rhyolite? Flow-foliated	Sparse plag phenocrysts	Mild. Hornf/silicific. Vesicles/vugs with epid, chl, py, act. Rich in py	Intrusive
WP-1525	Selva Alegre	6693	95948	Andesitic lava/intrusive	Plag + amph phyric	Mild. Amph to act, chl, sphene, opaq. Granoblast qtz patches. Hornfels?	Portovelo
WP-1530	Paccha	6599	96013	Granodiorite. Matrix granoblastic	Zoned plags	Fresh. Mafics to amph + bt	Intrusive
WP-1532	Paccha	6600	96005	Porphyritic microdiorite	Plag + amph phyric	Moderate. Amphs to chl, act, opaq. Many chl inclusions along plag fractures	Intrusive
WP-1537	Zaruma	6610	95863	Andesite	Feld + amph phyric	Moderate. Ab chl + epid + clay? Veinlets of K-feld? + py + epid	Portovelo
WP-1538	Zaruma	6596	95869	Andesite	Plag + mafic phyric	Moderate. Ab chl. Plag to calc + epid. Mafic to chl	Portovelo
WP-1539	Zaruma	6587	95869	Basaltic andesite. Flow foliated	Plag, mafic-phyric. Ab opaq ore	Mild. Mafic to chl. Ab zeolite vugs. Plag to chl + calc	Portovelo
WP-1544	Santiago	6732	95936	Medium grain granodiorite	Zoned plag + bt? + qtz + amph	Mild. Bt to chl + calc + epid. Plag to calcite	Intrusive
WP-1545	Santiago	6721	95931	Hornfelsed volcanic rock. Variable grain size		Intense. Granoblastic. Qtz with ab andalusite? Common musc also	Portovelo
WP-1548	Zaruma	6623	95895	Andesitic tuff	Andesite lithics. Sparse cpx	Moderate. Much chl + epid. Spots of radiating zeolite?	Portovelo
WP-1550	Santiago	6694	95778	Schist	Qtz/musc	Mild. Musc to chl	Metamorphic
WP-1551	Catamayo	6708	95759	Rhyolite	Plag + mafic-phyric	Mild. Devitrified. Plag fresh. Mafic to chl	Intrusive
WP-1553	Santiago	6745	95767	Quartzite	Sparse plag + zircon + schist frags	Fresh. Slight sericite alt of plag	Alamor
WP-1556	Catamayo	6859	95611	Rhyolite?		Intense. Several phases of silicification including large nodules	Intrusive
WP-1557	Santiago	6673	95884	Andesitic lithic tuff	Rich in lithics, felds + mafics	Mild. Propylitic. Mafics to chl + epid. Plag to epid. Matrix to chl + sphene	Portovelo
WP-1558	Selva Alegre	6829	96016	Andesitic/dacitic crystal tuff	Ab plag + horn + sparse qtz	Mild. Mainly fresh. Some mafics to chl + epid + calc	Saraguro
WP-1568	Girón	6947	96627	Quimsacocha rhyolite?		Intense silicification. Vugs. Much limonite	
WP-1578	Paccha	6517	96108	Hydrothermal rock		Quartz + micaceous low birefring min. prom. cleav. perpendicular to {001}	
WP-1580	Paccha	6514	96088	Acid tuff	Ab small lithics	Moderate. Ab clay alt. Clusters of zoisite	Portovelo

Sample	Sheet	UTMX	UTMY	Rock type	Minerals	Alteration	Unit
WP-1581	Paccha	6518	96079	Tuff/rhyolite		Intense. Silicific. Leached felds with euhedral qtz. Qtz, tourm, limon, veins	Portovelo
WP-1583	Paccha	6525	96077	Rhyolitic tuff	Ab. qtz crystals	Strong. Hydrothermal. All plag to sericite. Chl veinlets. Silicification	Portovelo
WP-1586	Paccha	6563	96089	Andesitic/dacitic lithic tuff		Strong. Potassic. Ab diss + veinlets bt, chl. Plag phenocrysts to py, qtz, epid	Portovelo
WP-1592	Paccha	6559	96055	Dacite and tuff		Moderate. Potas. Ab diss amph, py, epid, chl, py patches. Silicific or recrystal	Portovelo
WP-1593	Paccha	6546	96028	Amphibolite	Amph + qtz + feld + cpx. Poikilitic cpx	Mild	Amphibolite
WP-1594	Paccha	6528	96024	Granodiorite		Moderate. Potassic. Diss bt + epid + py + chl. Small amount of tourm	Intrusive
WP-1598	Paccha	6487	96026	Intrusive	Plag + mafic + bt phyric	Strong. Plag to clay. Bt to stilp + chl. Qtz veinlets	Intrusive
WP-1599	Paccha	6464	96083	Breccia. All clasts same	Tourm matrix	Intense. Musc, tourm, limonite. Silicified. Clasts of metamorphic or volcanic rocks?	Hydrothermal
WP-1600	Paccha	6471	96060	Coarse tonalite	Plag, qtz, amph, bt. Fine groundmass	Fresh. Slight alt of bt to chl	Intrusive
WP-1627	Zaruma	6557	95901	Lava/crystal tuff?	Mafic + plag crystals. Foliated matrix	Strong propyl. Matrix to chl, calc. Mafic to chl, calc. Plag to calc, clay	Portovelo
WP-1628	Selva Alegre	6737	95993	Andesite. Similar to 1630	Amph + plag phyric	Mild. Amph to chl + calc. Plag to calc + clay/sericite + chl	Intrusive
WP-1630	Selva Alegre	6738	95994	Andesite/intrusive. Similar to 1628	Plag, cpx, amph, bt, qtz phyric	Moderate Crystallization of matrix. Plag fresh	Intrusive
WP-1631	Selva Alegre	6736	95988	Microdiorite?	Plag + mafic phyric	Intense. Qtz, sericite, chl. Mafic to chl. Coarse tourm, qtz. Granoblastic qtz	Intrusive?
WP-1633	Selva Alegre	6716	95980	Dacite. Flow-foliated	Sparse amph + plag + qtz phyric	Mild. Patchy devitrification	Saraguro
WP-1634	Paccha	6512	96012	Andesitic/dacitic lithic tuff	Ab plag, fewer qtz crystals. Sparse lithics	Mild. Mafics to chl + epid. Plag to clay	Portovelo
WP-1641	Zaruma	6439	95903	Non-weld coarse vitroclast rhyo tuff.	Pumice + qtz crystals	Mild. Devitrification	Saraguro
WP-1643	La Avanzada	6378	96063	Andesitic/dacitic lithic tuff	Sparse welded tuff clasts	Moderate. Silicified. Chl + pyrite. Plag to clay/sericite	Saraguro
WP-1646	Ponce Enríquez	6643	96557	Basalt. Variolitic	Cpx + plag. Glassy matrix	Mild. Glass to chl	Saraguro
WP-1649	Ponce Enríquez	6618	96583	Hornfelsed tuff/sediment		Strong. Much sericite/musc	Hornfels
WP-1652	Ponce Enríquez	6603	96599	Tenguelillo. Coarse tonalite	Plag + qtz + mafics	Moderate. Weak shear. Strained qtz. Narrow zones of act. Mafics to chl + act	Intrusive
WP-1653	Ponce Enríquez	6601	96598	Gabbro/diorite	Coarse. Horn + plag	Mild. Amph to chl. Plag cloudy	Intrusive
WP-1653B	Ponce Enríquez	6601	96598	Tenguelillo. Calc-schist	Brittle grain reduct. Epid, calc, musc	Fresh	Metamorphic
WP-1657	Ponce Enríquez	6614	96602	Rhyolitic tuff	Ab. qtz crystals. Sparse lithics	Strong. Hornfels. Potassic. Diss bt. Poikilitic amphib. Granoblastic matrix	Bella Rica
WP-1660	Ponce Enríquez	6625	96618	Acid tuff?	Large euhedral qtz crystals	Strong. Hornfels. Coarse granoblastic qtz + musc + clinozoisite	Hornfels
WP-1661	Ponce Enríquez	6595	96635	Acid tuff	Sparse large shards. Large qtz crystals	Strong silicification/recrystallization. White mica in matrix	Bella Rica
WP-1664	Ponce Enríquez	6564	96624	Chanchán gabbro.	Sub-ophitic cpx + zone plag	Mild. Epid + chl. Cloudy plag	Intrusive
WP-1666	Ponce Enríquez	6435	96611	Chanchán fine gabbro/diorite. Variolitic	Horn + plag	Mod. Propylitic. Ab epid + chl. Amphs and plag cloudy	Intrusive
WP-1667	Ponce Enríquez	6434	96612	Chanchán microgabbro. Variolitic	Plag, amph. Plag corroded	Mild. Interstitial chl may be alterated glass. Epid	Intrusive
WP-1668	Ponce Enríquez	6436	96613	Chanchán microdiorite. Variolitic.	Plag + amph	Mod. Calc + epid + chl. Large vugs with epid + tourm + pyrite	Intrusive
WP-1670	Ponce Enríquez	6486	96676	Chanchán gabbro/diorite. Flow foliation	Plag + cpx	Mild cpx to amph + chl	Intrusive
A-1419	Yaritzagua	6974	96392	Welded tuff	Plag + qtz + bt	Very fresh. Some plag to calc	Jubones
WPFIFRR	Santiago	6830	96920	Rhyolite? Fierro Urcu	Qtz phenocrysts	Intense silicification. Veinlets of limonite + epid	Intrusive
BÑ-213	Santa Isabel	6860	96437	Rhyolite. Flow foliation	Plag + qtz + bt phenocrysts	Fresh	Intrusive?

APPENDIX 4 OF REPORT:

GEOLOGY OF THE WESTERN CORDILLERA
OF ECUADOR
BETWEEN 3°00’ AND 4°00’ S

MAGNETIC SUSCEPTIBILITY



GEOLOGICAL INFORMATION MAPPING PROGRAMME
(LOCATION OF MAP 1 AREA)

QUITO, 1997

Table 1. Kappameter (apparent magnetic susceptibility emu) and scintillometer readings

Map sheet	UTMY	UTMX	Sample	TC1 (cps)	TC2 (cps)	K (cps)	U (cps)	Th (cps)	k (emu)	Rock type
Ponce Enríquez	9651500	658700	8						0.14	Acid tuff
Ponce Enríquez	9650600	659400	8						8.1	Granodiorite
Santa Isabel	9636300	676300	10	310.6	77.1	29.9	2	2.3	2.4	Jubones Tuff
Uzhcurrumi	9634700	663500	14	158.1	77.8	13.1	1.1	0.8	32.9	Diorite
Uzhcurrumi	9632700	654100	21	78.7	12.3	1.5	0.9	0.5	29.5	Diorite
Uzhcurrumi	9632800	657300	23	302.5	102.4	12	3.3	1.8	0.41	Tuff breccia
Santa Isabel	9631900	680600	114	152.7	61.8	6.3	2	0.6	4.62	Jubones Tuff
Machala	9635400	632400	176	227.3	101.9	8.3	2.6	0.8	4.2	Acid Tuff
San Fernando	9651800	679300	233	91.2	20	7.5	1.1	0.6	55	Granodiorite
Ponce Enríquez	9650900	661900	275						10.7	Dacitic tuff
Yaritzagua	9643100	698200	278	128.3	92.7	19.9	2.4	0.7	15.9	Andesitic tuff
Manú	9629300	690700	298	251.2	80.3	15.4	1.6	0.6	14.9	Dacitic tuff
Santa Isabel	9647400	690800	326						17.6	Microdiorite
Ponce Enríquez	9658900	644800	452	28.8	14.1	4	0.8	0.4	25.4	Basalt
Manú	9629700	690200	509	203.9	47.6	19	2.4	0.6	5.77	Pumice tuff
Manú	9620300	681700	620	121.7	28.5	2	1.2	0.8	19.2	Andesite
Manú	9614400	679200	623	312.2	61	5.5	2	1.1	0.28	Gneiss
Manú	9614400	672700	717	236.5	48.6	4.5	1.1	0.3	24.3	Andesitic/dacitic lava
Selva Alegre	9612700	671300	718	203.2	48.5	3.1	2.5	0.7	2.7	Pumice tuff
Zaruma	9590700	651700	750	163.4	46	3.5	1.7	0.6	10.4	Dacitic tuff
Zaruma	9590400	649800	751	103.6	94.5	9.6	1.9	1.1	0.21	Acid tuff
Zaruma	9591600	650200	765	170.3	93.8	13.5	1	0.4	10.2	Acid tuff
Yaritzagua	9647600	706600	766	105.3	81.5	9.8	2.1	0.7	7.88	La Paz Tuff
Chaucha	9669300	688700	773	206.6	112	9.3	1.8	0.8	13.7	Jubones Tuff